CONFERENCE

PROCEEDINGS BOOK

ISPEC GLOBAL CONGRESS ON INTERDISCIPLINARY SCIENCE AND SCIENTIFIC RESEARCHAPRIL 27 APRIL 3 MAY, 2026 ROME, ITALY

2026



Editors

Prof. Dr. Tünay KARAN

Prof. Dr. Seyithan SEYDOŞOĞLU

ISPEC GLOBAL INTERDISCIPLINARY SCIENCE AND SCIENTIFIC RESEARCH CONGRESS (ISPEC-GISRC)

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ISPEC GLOBAL INTERDISCIPLINARY SCIENCE AND SCIENTIFIC RESEARCH CONGRESS (ISPEC-GISRC)

APRIL 27 - MAY 3, 2026 / ROME, ITALY

CONFERENCE

PROCEEDINGS BOOK

(Abstracts & Full Texts)

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EVALUATION PROCESS and POLICIES

All applications have undergone double blind peer review process. In addition, cach paper was accepted and the process of publishing in the book was carried out through editorial oversight.

The published papers were presented and discussed at the meting. Full texts and abstracts published in accordance with the Symposium Policy have been prepared in accordance with ethical rules and APA standards. Authors of all papers are both ethically and legally responsible.

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ISPEC GLOBAL INTERDISCIPLINARY SCIENCE AND SCIENTIFIC RESEARCH CONGRESS (ISPEC-GISRC)

APRIL 27 - MAY 3, 2026 / ROME, ITALY

CONGRESS PROGRAM

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Face to Face / Hotel La Giocca	
28.04.2026	**HALL-1 / SESSION-1**
ITALY LOCAL TIME: 19:00-21:00	

HEAD OF SESSION: Assoc. Prof. Dr. Yeşim AYDOĞAN

Authors	Affiliation	Presentation Title
Sevgi Durna Daştan	*Sivas Cumhuriyet University*	Scientific Approaches in Beekeeping, Research & Development and Application Center Experiences
Muhammad Lomanov Serap Güleç Keskin	*Ondokuz Mayıs University*	The Everyday Production of Stigma in Multiple Sclerosis: Actions, Discourses, and Impressions
Muradiye Polat Serap Güleç Keskin	*Ondokuz Mayıs University*	Morning Meetings in Child and Adolescent Addiction Treatment Units: The Role of Structured Day Initiation in Therapeutic Milieu and Clinical Regulation
Yeşim Aydoğan	*Inönü University*	The Use of Waste Materıals in Experimental Printmaking: A Sustainable Approach
Ali Onur Kaya Mert Can Emre Berkay Emre İbrahim Halil Mutlu	*Yozgat Bozok University*	Comparative Evaluation of Corrosion Performance of TiO_2 and Polymer-Modified TiO_2 Coatings on Low-Carbon Steel and Az31 Magnesium Alloy
Yeşim Aydoğan Ayşegül Kaçmaz	*Inönü University*	The Use of Natural Forms in Experimental Painting: Sustainability and Formal Analysis
F. Özge Uysal Önder Uysal	*University of Napoli Federico Iı*	Evaluation of Process Performance in Microalgae-Based Wastewater Treatment Using Artificial Intelligence
Mahir Uzun Derya Abak	*Inönü University*	Determination of the Optimal Fixation of the Mandibular Bone from Different Angles Using Numerical and Experimental Data
Mahir Uzun Caner Bulut	*Inönü University*	Production of Ceramic Reinforced Cocufeni High Entropy Alloys by Powder Metallurgy Method and Investigation of Their Hardness Behavior
Fatma Göç Hilal Bacanak	*Tokat Gaziosmanpaşa University*	Not All Phenolıcs Are Equal: Structural Determınants of Cholinesterase Inhibition

(All speakers required to be connected to the session 10 min before the session starts)
Moderator is responsible for ensuring the smooth running of the presentation, managing the group discussion and dynamics.

Face to Face / Hotel La Giocca		
28.04.2026	**HALL-2 / SESSION-1**	
ITALY LOCAL TIME: 19:00-21:00		
HEAD OF SESSION: Prof. Dr. Çetin KARADEMİR		
Authors	**Affiliation**	**Presentation Title**
Emine Sema Çetin Berna Keles	*Yozgat Bozok University*	Sustainable Viticulture and Local Development in Bahadin Town (Sorgun/Yozgat Province): A Survey Study
Emine Sema Çetin Emin Elibol Berna Keles	*Yozgat Bozok University*	The Effect of Nanoparticle Application on Secondary Metabolite Production in the 'Michele Palieri' Grape Cultivar
Mustafa Gültekin Şeyda Çavuşoğlu Erkan Eren	*Van Yüzüncü Yıl University*	Effects of Chitosan Coatings on Color and Gas Composition of King Oyster Mushroom (*Pleurotus eryngii*) Under Modified Atmosphere Conditions
Şeyda Çavuşoğlu	*Van Yüzüncü Yıl University*	Microbial Modulation of Ethylene Biosynthesis in Climacteric Fruits: Mechanistic Insights and Postharvest Applications of ACC Deaminase-Producing PGPR
Gülbahar Tazegül Mevlüde Beyza Bayhan Sabriye Belgüzar	*Tokat Gaziosmanpaşa University*	Investigation of the Control Potential of Microbial Fertilizers Against Tomato Bacterial Canker and Wilt Disease
Osman Alperen Güven Mevlüde Beyza Bayhan Sabriye Belgüzar	*Tokat Gaziosmanpaşa University*	Determination of the Antagonistic Effects of Plant Growth-Promoting Rhizobacteria Against *Rhizoctoniasolani* Caused Pepper Root Rot
Çetin Karademir Burhan Uraz	*Siirt University*	Effect of Foliar Application of Boron and Zinc on Cotton Yield and Physiological Characteristics-I
Çetin Karademir Burhan Uraz	*Siirt University*	Effect of Foliar Application of Boron and Zinc on Cotton Quality Characteristics-II
Tuğba Çakar Şeyda Şimşek Mustafa Alkan	*Tokat Gaziosmanpaşa University*	Evaluation of Integrated Pest Management Strategies Against Two-Spotted Spider Mite (*Tetranychus urticae*)
Merve Özben Emine Karademir	*Siirt University*	The Effects of Ascorbic Acid on Plants
Ömer Kardaş Emine Karademir	*Siirt University*	The Effects of Shading on Fiber Yield and Fiber Quality in Cotton
Tuğba Çakar Şeyda Şimşek	*Tokat Gaziosmanpaşa University*	Environmental Determinants of Population Dynamics of Two-Spotted Spider Mite (*Tetranychus urticae*)
Şeyda Şimşek Tuğba Çakar Mustafa Alkan	*Yozgat Bozok University*	Plant-Based Insecticides in Stored-Product Pest Management: Current Approaches and Future Prospects
Şeyda Şimşek Tuğba Çakar	*Yozgat Bozok University*	Insecticidal Potential of *Cannabis sativa* L. Against Pest Insects
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Face to Face / Hotel La Giocca	
28.04.2026	**HALL-3 / SESSION-1**
ITALY LOCAL TIME: 19:00-21:00	

HEAD OF SESSION: Prof. Dr. Emine Sema ÇETİN

Authors	Affiliation	Presentation Title
Hanife Doğan	*Necmettin Erbakan University*	Lifelong Physical Activity: The Most Powerful Strategy in Preventive Medicine
Çağrı Çağlar Sinmez Gökçe Şeker Karatoprak Harun Hızlısoy Selen İlgün Esra Köngül Şafak Fatih Doğan Koca Tünay Karan Mükerrem Betül Yerer	*Erciyes University*	Composition Analysis of *Viscum album* (Mistletoe) Leaf Extracts from Various Host Plants: Antibacterial, Antioxidant, and Cytotoxic Properties and Potential Usability as Organic Component for the Synthesis of Cu-Based Hybrid Nanoflower
Büşra Nur Ceylan Şeyma Kaya Nilgün Öncül	*Muğla Sıtkı Koçman University*	A Plant-Based Beverage Enriched with *Spirulina platensis*
Şeyda Kaya Sevgi Durna Daştan	*Gaziantep Islam Science and Technology University*	Anti-Inflammatory Effects of *Goji berry* (*Lycium barbarum*) Extracts from the Province of Sivas
Zehra Deniz Çırak	*Inonu University*	Magnetically Responsive Polybmer Matrix Nanocomposites
Fatih Çelik Kemal Çelik	*Mlcc, Dubai, Birleşik Arap Emirlikleri*	Comparison of Geoid Heights Calculated from Global Geopotential Models with Tg-20 in the Kackar Mountains Region
Fatih Çelik Kemal Çelik	*Mlcc, Dubai, Birleşik Arap Emirlikleri*	Comparison of Bouguer and Free-Air Anomalies Calculated from Global Earth Potential Models in the Kaçkar Mountains: Statistical and Spectral Analysis
Gizem Aslan Nilgün Öncül	*Muğla Sıtkı Koçman University*	A Traditional Grape-Based Food: Üzüm Köftesi Chemical
Emine Endes Selda Yüzer Alsaç	*Yozgat Bozok University*	The Effect of Medical Procedure Fear on Psychosocial Symptoms in a Hospitalized Child

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Face to Face / Hotel La Giocca	
28.04.2026	**HALL-1 / SESSION-2**
ITALY LOCAL TIME: 21:30-23:30	

HEAD OF SESSION: Prof. Dr. Çağrı Çağlar SİNMEZ

Authors	Affiliation	Presentation Title
Şeyda Kaya	*Gaziantep İslam Bilim Ve Teknoloji University*	Network Pharmacology: Key Data Sources and Analysis Tools Used for Drug Discovery
Tünay Karan Murat Çakır	*Yozgat Bozok University*	Advantages of The Cecal Ligation and Puncture Method in Experimental Sepsis Models
Tünay Karan Murat Çakır	*Yozgat Bozok University*	The Role of The Endocannabinoid System in the Pathophysiology of Sepsis: Therapeutic Potential of Cb1 and Cb2 Receptor Modulation
Şimal Tuncina Akgünlü Murat Çakır İlknur Alkan Kuşabbi Özgür Zeliha Karaahmet Erhan Arif Öztürk Emre Adıguzel	*Yozgat Bozok University*	Effects of Aerobic Exercise on Serum Myokine Levels in Patients with Ischemic Stroke
Murat Çakır Semanur Fırat Ali Aydın Burak Bircan	*Yozgat Bozok University*	Effect of Urb597 on Kidney Damage in Sepsis Model Induced by Cecal Ligation and Puncture
Sibel Erdem	*Muğla Sıtkı Koçman University*	Effects of Time-Restricted Feeding and Intermittent Fasting on Insulin Resistance: A Systematic Review of Randomized Trials
Özlem Kaya	*Uşak University*	Analysis of Gen Z Behaviors in Sustainable Fashion Consumption
Özlem Kaya	*Uşak University*	Digital Fashion and the Metaverse: The Future of Virtual Garment Design
Tarık Baydar Naim Aslan Hüseyin Ertap Seydi Doğan	*Balıkesir University*	Structural and Morphological Properties of Nd-Fe_3O_4 Nanopowders

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Face to Face / Hotel La Giocca	
28.04.2026	**HALL-2 / SESSION-2**
ITALY LOCAL TIME: 21:30-23:30	

HEAD OF SESSION: Prof. Dr. Sevgi DURNA DAŞTAN

Authors	Affiliation	Presentation Title
Selma İpek	*İnönü University*	A New Paradigm for Modern Society: Ulrich Beck's Risk Society Theory
Nuray Girginer Damla Aydın	*Eskişehir Osmangazi University*	Current Approaches and Methodological Developments in Sentiment Analysis: A Literature Review
Makbule Özdemir Gülten Şentürk Sipahi	*Kırşehir Ahi Evran University*	Generative AI as a Design Assistant in Early Architectural Design Stage: Opportunities and Limitations
Gülten Şentürk Sipahi Makbule Özdemir	*Kırşehir Ahi Evran University*	A Qualitative Study on Digital Transformation and User Perception in Urban Squares
Gamze Çoban Elif Çam Şule Sinem Sürdem	*Karamanoğlu Mehmetbey University*	A Fractal-Based Quantitative Compatibility Model for New Addition in Historic Contexts
Nuray Girginer Damla Aydın Füsun Yenilmez	*Eskişehir Osmangazi University*	Applications of Sentiment Analysis in Customer Experience Management in Businesses
Sümeyye Yıldız	*Siirt University*	An Assessment of the Relationship Between Mysticism and Mental Health
Hüseyin Yüner	*Yozgat Bozok University*	Nefes And Deyis Forms In The Alevi-Bektashi Tradition: A Turkish Religious MusicCentered Analysis And AI-Supported Cultural Transmission
Berna Yüner Hüseyin Yüner	*Yozgat Bozok University*	Empowering University Students Through Peer Support: A Community-Led Research and Action (Clra) Approach
Semra Uzun	*Munzur University*	Love Trauma and Broken Hearts Syndrome in &Quot; the Madonna in a Fur Coat

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28.04.2026	**HALL-3 / SESSION-2**
ITALY LOCAL TIME: 21:30-23:30	

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HEAD OF SESSION: Prof. Dr. Rüveyde TUNÇTÜRK

Authors	Affiliation	Presentation Title
Hüseyin Kaya Rukiye Kılıç	*Siirt University*	The Effect Of Salicylic Acid Priming On Germination Characteristics Of Sugar Beet (*Beta Vulgaris*) Seeds Under Cadmium Toxicity
Rukiye Kılıç Emine Karademir Çetin Karademir	*Siirt University*	Investigation Of The Effects Of Temperature On Different Growth Stages In Cotton
Ali Endes	*Yozgat Bozok University*	Multifunctional Roles of *Trichoderma* spp. in Strawberry Agroecosystems: Mechanisms, Plant–Microbe Interactions and Implications for Sustainable Disease Management
Ali Endes	*Yozgat Bozok University*	Fusarium Oxysporum in Strawberry Production Systems: Etiology, Symptomatology, Epidemiological Complexity and Integrated Management Frameworks
Dilan Altun Emine Karademir	*Siirt University*	The Effect of Melatonin on Abiotic Stress Factors in Cotton
Dilan Altun Emine Karademir	*Siirt University*	Low Temperature Stress and Its Physiological Effects in Cotton
Kader Uygun Rüveyde Tunçtürk	*Van Yuzuncu Yıl University*	Determination of the Effect of Ontogenetic Variability on Dualex Values in Sage *(Salvia officinalis* L.)
Nagehan Desen Köycü	*Tekirdağ Namık Kemal University*	Toxicological Effects of Fungicide Use on Human Health and Environment: Risk Assessment Methods
Aysen Koç Hatice Uçaral Hayran	*Yozgat Bozok University*	Rosehip Selection in Yozgat, Türkiye: Fruit Characteristics
Aysen Koç Hatice Uçaral Hayran	*Yozgat Bozok University*	Rosehip Selection in Yozgat, Türkiye: Morphological Characteristics
Rüveyde Tunçtürk Murat Tunçtürk Muhammed Said Yolci	*Van Yüzüncü Yıl University*	Determination of Photosynthetic Pigments and Biochemical Contents of Hyssop (*Hyssopus officinalis* L.) Microgreens
Rojin Özek	*Kırıkkale University*	Tritordeum Cultivation
Rojin Özek	*Kırıkkale University*	Alternative Grain Sources: Pseudograins

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27.04.2026 / ONLINE / SESSION-1 / HALL-1

Roma Local Time: 08:00-10:00 | Ankara Local Time: 09:00-11:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. Defne Öcal KAPLAN

Authors	Affiliation	Presentation Title
Cansu Kara Ayşe Çinpolat Ebru Arslanhan Gökhan Uyanık	*Hatay Mustafa Kemal University*	A Case of Obstructive Dystocia Caused by Transmissible Venereal Tumour (TVT) in a Bitch
Hanife Doğan Hanife Abakay	*Necmettin Erbakan University*	The Relationship Between Disease Duration, Pelvic Floor Symptoms, and Quality of Life in Women with Scleroderma
Hanife Doğan Hanife Abakay	*Necmettin Erbakan University*	The Relationship Between Pelvic Floor Symptoms, Depression Levels, and Quality of Life in Children Diagnosed with Voiding Dysfunction
Defne Öcal Kaplan	*Kastamonu University*	Proactive Protection in Fall Risk Management Through Artificial Intelligence-Supported Physical Activity Applications in Geriatric Individuals
Duygu Sultan Öge Hanife Doğan Fatma Kılıç Hamzaoğlu Türkan Akbayrak	*Meram State Hospital*	The Effect of Different Methods for Teaching Pelvic Floor Muscle Contraction on Abdominal and Pelvic Floor Muscle Activation Response: BF-EMG Analysis Response: BF-EMG Analysis
Defne Öcal Kaplan Irmak Karabaş Gökhan Şanal	*Kastamonu University*	Comparative Analysis of Q Angle and Postural Parameters in Female Soccer and Rugby Players
Serkan Bentli Şevval Gelen	*Malatya Turgut Özal University*	Iddsi and Dysphagia Management
Serkan Bentli Fatma Sena Babuç	*Malatya Turgut Özal University*	Bone Marrow Transplantation and Nutritional Strategies
Elif Çam Gamze Çoban Havva Alkan Bala	*Karamanoğlu Mehmetbey University*	Definition–Design Translation as Artificial Intelligence: The Transformation of Capsule Living, Portable Housing, and Nomadic Architecture into Innovative Prototypes
Mehmet Turgut Melek Hilal Kaplan Zekiye Eroglu	*Nevsehir Hacı Bektaş Veli University*	Comparison of Intraoral Scanner Accuracy in Full Arch and Regional Areas
Duygu Sultan Öge Hanife Doğan Fatma Kılıç Hamzaoğlu Türkan Akbayrak	*Meram State Hospital*	Comparison of Two Different Assessment Methods in Terms of Sensitivity to Training-Induced Changes in Pelvic Floor Muscle Strength: Digital Vaginal Palpation and Perineometer

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27.04.2026 / ONLINE / SESSION-1 / HALL-2

Roma Local Time: 08:00-10:00 | Ankara Local Time: 09:00-11:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. Süleyman ÖNER

Authors	Affiliation	Presentation Title
Aysun Şahin Azize Şahin	*Duzce University*	Algorithmically Objectified: The Datafied Child Consumer in Ai- Driven Marketing Ecosystems
Aysun Şahin Azize Şahin	*Duzce University*	Engineered Choices: Algorithmic Nudging, Behavioral Vulnerability, and the Child Consumer in Ai-Driven Marketing Environments
Aras Yolusever	*Istanbul Kültür University*	Institutional Economics Under Stress: Did the Trump Presidency Falsify Institutional Theory?
Murat Güngül	*Eskişehir Osmangazi University*	The Role of Solar Energy Systems in Reducing Energy Costs in Agricultural Enterprises
Ömer Büyükbaş Hamdi Ayyıldız	*Kahramanmaraş Sütçü Imam University*	A Multi-Criteria Mediterranean Diet Sustainability Index for Turkish Households: An Entropy-Topsis Framework Integrating Carbon, Nutrition, Cost, and Waste Sensitivity
Hamdi Ayyıldız Ömer Büyükbaş	*Kahramanmaraş Sütçü Imam University*	Does Mediterranean Diet Adherence Always Mean Lower Kitchen Carbon Footprints? The Eroding Role of Food Waste and Consumer Behaviour
İlknur Çevik Tekin	*Selçuk University*	Algorithmic Human Resources Management: Ethics and Trust
Süleyman Öner	*Muğla Sıtkı Koçman University*	Shrimp Food
Süleyman Öner	*Muğla Sıtkı Koçman University*	Clam Food

(All speakers required to be connected to the session 10 min before the session starts)
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27.04.2026 / ONLINE / SESSION-1 / HALL-3

Roma Local Time: 08:00-10:00 | Ankara Local Time: 09:00-11:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. Mahmut TUTAM

Authors	Affiliation	Presentation Title
Yusuf Ahmed Tijjani Zaharaddeen Khamis Shafi'e Sakanau	*Ahmadu Bello University Zaria*	Effect of Risk Committee Independence on Financial Performance of Commercial Banks in Nigeria
Carla Santos Cristina Dias	*Nova University of Lisbon*	Representation Systems and the Mitigation of Probabilistic Fallacies
Babita Gupta,	*Institute of Technology and Management Gida*	Revolutionizing Cancer Diagnosis: The Potential of 3D Printed Nanosensors
Mark Anthony N. Polinar, Caren C. Sasan Regin M. Suarez	*St. Cecilia's College-Cebu,*	Beyond the Classroom: Public School'S Lived Experiences in Handling Advisory Classes
Dan Cong Thaı Anh Hoang Huynh Quyen Xuan Thi Do	*Can Tho University,*	Using Journal Articles to Enhance Graduate Students' Understanding of Community-Based Educational Management: An Article-Based Learning Approach
Jafor Chowdhury Sabiha Nusrat Kazi Akib Hasan Sadia Afrin Helal Murshed	*University of North Texas Health Science*	Mapping the Global Resistome: Ecological and Evolutionary Pathways of Antimicrobial Resistance
Kaoutar Ouahibi Ikram Mennas El Mostafa Benharaf Radouan Elharkaoui A.Arif Mohammed El Idrissi	*Sultan Moulay Slimane University,*	Tuning the Optoelectronic Properties of A–D–A Benzothiadiazole Non- Fullerene Acceptors via Cyano Substitution: A DFT/TD-DFT Study
Dr. Saima Shaheen Dr. Nabila Sher Dr. Kalsoom Tariq	*Khyber Girls Medical College*	Thyroid Hormone Levels and Their Association with Plasma Zinc Levels Among Adolescent Afghan Refugees; A Cross-Sectional Study
Lulzime Ballazhi Edita Alili-Idrizi Merita Dauti Sihana Ahmeti-Lika Drita Havziu-Yzeiri Hanife Rustemi-Ahmeti Arbnora Qahili-Nazifi Gjylai Alija	*University of Tetovo*	Ace Inhibitors Vs Arbs: A Comparative Analysis of Clinical Indications and Therapeutic Use

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27.04.2026 / ONLINE / SESSION-1 / HALL-4

Roma Local Time: 08:00-10:00 | Ankara Local Time: 09:00-11:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

4HEAD OF SESSION: Muthuramalingam. M

Authors	Affiliation	Presentation Title
Elmyra Zerlina Ratna Septiyanti	*University of Lampung*	Do Men And Women Spend Differently? Evidence from Urban and Rural Households
Jan Sadur Rahman Moon Ismat Ara Begum	*Affiliated with University of Rajshahi*	Multifunctional Roles of *Trichoderma* spp. in Sustainable Agriculture, Biotechnology, and Environmental Management
Marina S.T. Stojanova Dragutin A. Djukic Monika Stojanova Milos Rabrenovic	*University of Ss. Cyril and Methodius*	Foliar Application of Nano-Zinc in Vegetable Crops: Mechanisms, Efficiency, and Agronomic Implications
Monika Stojanova Sani Demiri Olga Popovska Arita Sabriu Haxhijaha	*Mother Teresa University*	Nanotechnology in the Food Industry: Innovations for Safety, Quality, and Sustainability
Moses Adeolu Agoı Samuel Olayiwola Ajaga Oluwanifemi Opeyemi Agoı Success Eniola Ogboye	*Lagos State University of Education*	Evaluating the Economic Feasibility of Transitioning from Natural Gas to Biogas in Modern Markets
Shirinova Lala Shirinova Nargiz	*Azerbaijan Medical University*	Comparative Analysis of Bioecological and Clinical-Epidemiological Characteristics of Cutaneous and Visceral *Leishmaniasis* in the Lesser and Greater Caucasus Regions
Muthuramalingam. M Gomathy. E	*Bharath Institute of Higher Education and Research*	Green Pharmacy an Eco Friendly Approach in Modern Healthcare
Shama Islam Zubair Aslam Mohd Shoeb Shama Parveen S. S. Ashraf	*School of Engineering Sciences and Technology*	Radio-Frequency Plasma Polymerization of N,N-Dimethylaniline:Synthesis and Comprehensive Characterization of Thin Films
Pham The Hung Nguyen Thanh Thuy	*Dong Thap University*	Educational Ecosystems in Higher Education: A Strategic Orientation for Vietnamese Universities in the Digital Era
Jaayefar Fatima-ezzahra Dahmani Jamila	*Ibn Tofail University,*	Data Capitalization of Juniperus oxycedrus L.: Therapeutic and Pharmacological Valorization of a Medicinal and Aromatic Plant from the Mediterranean Region

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27.04.2026 / ONLINE / SESSION-1 / HALL-5

Roma Local Time: 08:00-10:00 | Ankara Local Time: 09:00-11:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Milos RABRENOVIC

Authors	Affiliation	Presentation Title
Muhammad Arslan Ashraf Rizwan Rasheed	*Government College University Faisalabad*	Taurine-Mediated Mitigation of Arsenic and Microplastic Toxicity in Broccoli via Functional and Microstructural Reprogramming
Milos Rabrenovic Monika Stojanova	*Montenegro Dance Sport Federation*	Digital Marketing Strategies for the Promotion of Gastronomic and Dance Festivals
Muhammad Usama Mahwish Salman Shahid Adeel Noman Habib	*Government College University Faisalabad*	Biochemical Exploration of Fungal-Derived Natural Colorants for Sustainable Textile Applications
Chaouquı Imane Moussadık Ali Anouzla Abdelkader Mabroukı Jamal Abroukı Younes	*Mohammed V University*	Principles and Applications of Density Functional Theory in Inorganic Chemistry: Key Challenges and Solutions
Temilade Afolasade Olatunji Olutunji Adetunji, Olaoye	*Federal Polytechnic*	Violence Without Spectacle: Slow Trauma in Half of a Yellow Sun and Song for Night
Olena Sierikova Vadym Babakin Andrii Derecha Larysa Derecha Yevheniia Kovkina	*Hon. Prof. M.S. Bokarius Forensic Science Institute*	Expert Examination of Liquid Hydrocarbon Storage Tank Damage
Olena Sierikova Olexander Yevsiukov Elena Strelnikova Kyryl Degtyariov	*Hon. Prof. M.S. Bokarius Forensic Science Institute*	Environmental Protection from Technogenic Objects under Earthquake and Explosion Effects
Aaditya Kumar Dwivedi Kamaljit Singh Riya Sharma	*Srm University*	Sustainable Investing and Risk- Adjusted Performance: Evidence from Indian Capital Markets
Zainib Razzaq Samreen Gul Khan Ayesha Riaz Tanzeela Riaz Mehr Un Nisa	*Government College University*	Bio-Oriented Synthesis and Molecular Docking Studies of 1,2,4-Triazole Based Derivatives as Potential Anti-Cancer Agents Against Hepg2 Cell Line

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27.04.2026 / ONLINE / SESSION-1 / HALL-6

Roma Local Time: 08:00-10:00 | Ankara Local Time: 09:00-11:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Muhammad ABID

Authors	Affiliation	Presentation Title
Muhammad Abid	*Government College University*	Improved Exponential Type Ratio Estimators Using Non-Conventional Location Parameters
Sarah Shahid	*Khyber Girls Medical College*	Evaluating Myocardial Performance and Arterial Blockages in Patients with a Family History of Cad
Mohd Kaif Abdur Rahman Qurratul Ain Bhavani Singh Abdul Hannan	*Aligarh Muslim University*	Empowering Women Through Climate-Smart Agriculture: Evidence from Rural Communities
Helal Uddin Israt Farzana Arshi Asikur Rahman Kawser Rukyaa Huda Priom	*Hajee Mohammad Danesh Science and Technology University*	Sustainable Waste-to-Energy (Wtw) Solutions for Urban Climate Resilience in South Asia
Helal Uddin Alamgir Hossain Sohag Ahasan Sharif Ibne Mizan Al Mahmud Motassin Billah Shehab	*Hajee Mohammad Danesh Science and Technology University*	Minimizing Material Waste in Automotive Manufacturing Through AI-Assisted Generative Design
Bousdıg Imane Loukılı Hayat Beqqour Dounia Achıou Brahim Ouammou Mohamed Alamı Younssı Saad	*University of Hassan II Casablanca*	Membrane Separation Processes in Water and Wastewater Treatment: Technologies, Challenges, and Future Directions
Clementina Hashimu Bulus Lokrit Loretta Gorip	*University of Jos*	Assessment of Parental Involvement in Children's Educational Development in Jos North Local Government Area of Plateau State, Nigeria
Ina Zela	*Mediterranean University of Albania*	What Does the Gutmann Method Reveal About Albania's Non-Observed Economy?
Irfan Bashir Yasira Waqar Afshan Naseem Aisha Sami Alams Shoaib Farhat Munir Sajid Masood Amna Yousaf Aqila Rafiq Faisal Anees Ghazala Ishrat	*University of Management and Technology*	Perceived Impact of Teacher's Behaviour on Student's Learning

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27.04.2026 / ONLINE / SESSION-2 / HALL-1

Roma Local Time: 10:30-12:30 | Ankara Local Time: 11:30-13:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Dilek Arslan ATEŞŞAHİN

Authors	Affiliation	Presentation Title
Dilek Arslan Ateşşahin Lütfiye Kadıoğlu Dalkılıç Semih Dalkılıç	*Fırat University*	Effect of *Heliotropium circinatum* on the Expression of Some Apoptotic Genes (Tp53, Bax And Bcl2) in Hepg2 and Mcf-7 Cell Lines
Dilek Arslan Ateşşahin Lütfiye Kadıoğlu Dalkılıç Semih Dalkılıç Abdullah Akman Rabia Yılmaz	*Fırat University*	Exploring the Therapeutic Properties of Elaeagnus Angustifolia: A Study on Its Antimicrobial, Antioxidant, and Anticancer Effect
Ceyhun Yücel Mustafa Boğa Salih Çelik	*Yozgat Bozok University*	Evaluation of the Golden Ratio and Feed Synergy in Ration Preparation: Impacts on Performance, Economy, Sustainability and Climate Change
Bahar Sözübek Mergül Öztürk	*Tekirdağ Namık Kemal University*	Evaluation of the Relationships Between Soil Properties, Plant Nutrition, and Dye Quality in Rubia Tinctorum L. Used in Textilie Dyeing: Current Status and Research Gaps
Mehmet Çakıroğlu Sedat Yiğit	*Kahramanmaraş Private Interest Specialised Rehabilitation*	Effects of Dual-Task Performance on Gait and Balance in Individuals with Lower Extremity Amputation
Mehmet Çakıroğlu	*Kahramanmaraş Private Interest Specialised Rehabilitation*	The Effects of Pain Expectation on Motor Performance and the Rehabilitation Process
Zeynep Demir	*Soil Fertilizer And Water Resources Central Research Institute*	Effects of Diatomıte and Soil Moisture Regime on Ionic Balance and Soil Chemical Properties in a Calcareous–Alkaline Soil
Utku Güner Aslıhan Dikmen Mustafa Elibol	*Trakya University*	Inclusive Education in the Age of Transformation: Nature- and Science-Based Approaches for Individuals with Special Needs
Onyekwelu, Chinyere Nkemakonam Ogbu, Onyinye Christiana	*Federal Polytechnic*	Evaluatıon Of Proxımate Ompositıonfunctıona And Sensory Properties Of “Garrı” Produced From Blends Of Cassava And Sweet Potatoes Fortıfied Wıth Afrıcan Yam Bean

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27.04.2026 / ONLINE / SESSION-2 / HALL-2

Roma Local Time: 10:30-12:30 | Ankara Local Time: 11:30-13:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. Naz MARDANI

Authors	Affiliation	Presentation Title
Gamze Yıldırım Alican Bahadır Semerci Mıne Kırkbınar Meltem Demirel Kars Fatih Çalışkan Ramazan Gönenci	*Necmettin Erbakan University*	In Vitro Evaluation of Cu-Doped Silicon Nitride Composites
Saffet Kılıçer Mustafa Mert Kılıç	*Artvin Çoruh University*	Manufacturing and Performance Analysis of a Reinforcement Connection Device Developed for Alternative Load-Path Continuity in Reinforced Concrete Structures
Hatice Gizem Şahin Fatih Eren Akgümüş Ali Mardani	*Bursa Uludag University*	Influence of Fiber Length, Fiber Content, and Aggregate Type on The Drying Shrinkage of 3d-Printable Concrete Mixtures
Murteda Ünverdi Selin Özteber Ali Mardani	*Bursa Uludag University*	Durability and Rheology Problems in Limestone Calcined Clay Cements (Lc3): Inconsistencies Between Laboratory Data and Field Realities
Veysel Kobya Yahya Kaya Yunus Kaya Ali Mardani	*Bursa Uludag University*	Effects of Molecular Chain Ratio of Pce-Based Grinding Aids on Flowability of Cementitious System
Naz Mardani	*Bursa Uludag University*	Conceptualization of the Exponential Function 2 X Using Cabri-Geometry Ii Plus in a Dynamic Geometry Environment
Hakan Basdogan Cihat Güner	*Erişler Food Ltd. R&D Centre*	Effects of Functional Fibers on Oil Uptake and Textural Properties in Legume-Based Noodles During Frying
Cihat Güner Hakan Basdogan	*Erişler Food Ltd. R&D Centre*	Interaction of Functional Ingredients and Processing Parameters in the Development of Low Glycemic Index Noodles

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27.04.2026 / ONLINE / SESSION-2 / HALL-3

Roma Local Time: 10:30-12:30 | Ankara Local Time: 11:30-13:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Ali Akbar FIROOZI

Authors	Affiliation	Presentation Title
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Digital Transformation in Geotechnical Engineering: Prospects for Smart Site Investigation and Ground Risk Management
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Sustainable Ground Improvement in Urban Development: A Critical Review of Strategy Selection and Long-Term Performance
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Bio-Inspired and Bio-Mediated Approaches in Geotechnical Engineering: Emerging Pathways for Sustainable Ground Stabilization
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Geotechnical Perspectives on Landslide Risk Governance: Integrating Engineering Judgment with Community Resilience
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Climate-Resilient Geotechnical Design for Expansive Soils: A Framework for Sustainable Infrastructure Adaptation
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Circular Economy Principles in Geotechnical Engineering: Reframing Earthworks, Materials Reuse, and Ground Sustainability
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Resilient Foundation Engineering Under Changing Environmental Conditions: A Geotechnical Perspective on Long-Term Adaptation
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Underground Urban Expansion and Geotechnical Risk: Rethinking Subsurface Planning for Sustainable Cities
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Artificial Intelligence in Geotechnical Engineering Decision-Making: Opportunities, Limits, and Responsible Pathways
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Geotechnical Resilience of Transport Corridors: Rethinking Subgrade, Embankment, and Slope Performance Under Future Stressors
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Geotechnical Engineering for Renewable Energy Infrastructure: Emerging Foundation and Ground Challenges in the Energy Transition
Ali Akbar Firoozi Ali Asghar Firoozi	*University of Botswana*	Uncertainty Communication in Geotechnical Engineering: Toward More Transparent and Resilient Design Practice

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27.04.2026 / ONLINE / SESSION-2 / HALL-4

Roma Local Time: 10:30-12:30 | Ankara Local Time: 11:30-13:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Nazmul Hasan ARFIN

Authors	Affiliation	Presentation Title
Rosemary Chiamaka Nzennwa Somtochukwu Chiagoziem Okafor	*University of Nigeria*	Comparative Analysis of Production Constraints Among Male and Female Cocoyam Farmers in Anambra State
Babita Gupta	*Babita Gupta*	Thermal-Sensitive Food Products for Therapeutic Applications
Denada Ahmeti Olta Llaha	*Sports University of Tirana*	Impact of Artificial Intelligence on Improving Teaching Processes in Higher Education: A Review
Elmehdi Majdi Hamza Marouani Soufiane Zerraf Said Belaaouad	*Hassan II University of Casablanca*	Synthesis, Crystallographic Characterization, and Theoretical Study of a Novel $(C_7H_8No_2)_2H_2P_2O_7$ Single Crystal
Nazmul Hasan Arfin	*Sylhet Agricultural University*	Effect of Seaweed Enriched Humic Acid on Growth and Yield of Bt. Brinjal (*Solanum melongena* L.)
Musa Mohammed Jimada Abdulrahman Ahmed Abdullahi Barkuta	*Dr. Umaru Sanda Ahmadu College of Education*	Assessment of Challenges of Procrastination Behaviour and Counselling Strategies Among Secondary School Students in Niger State, Nigeria
Miryam Chafik Ahmed Benjelloun	*Sidi Mohamed Ben Abdellah University*	Rethinking Co-Creation in the Age of Artificial Intelligence
Parvin Najafguliyeva Rauf Gasimov	*Azerbaijan Medical University*	Recurrent Hepatic and Peritoneal Echinococcosis: Surgical Strategy in Multiorgan Involvement
Olubiyo, O. Peter	*Adeyemi University of Education*	Ai-Driven Cataloguing and Classification Services in Academic Libraries in a Digital Economy
Fajun Nisha	Crescent Institute of Science and Technology	The Illusion of Choice: Are Our Decisions Really Our Own

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27.04.2026 / ONLINE / SESSION-2 / HALL-5

Roma Local Time: 10:30-12:30 | Ankara Local Time: 11:30-13:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Benedicto B. BALILO

Authors	Affiliation	Presentation Title
Benedicto B. Balilo	*Bicol University*	Community Perceptions of Youth-Led Sustainable Rural Development in Pamplona, Camarines Sur, Philippines
Masudul Islam Khan	*Daffodil International University*	Iron Uptake Regulation in Plants: Mechanisms and Pathways to Enhance Human Nutrition
Muhammad Safdar Syed Mohsan Raza Shah	*University of Education*	Unveiling Adaptive Components for Environmental Heterogeneity in Ipomoea Carnea Jacq
Fidelis Deborah Chindongnaan	*The Federal Polytechnic Ilaro Ogun State*	Navigating Cultural Nuances: Issues in French-to-English Translation
Anga, Peter Inalegwu	*Federal University of Technology*	Development and Implementation of a Virtual Chemistry Laboratory for Enhancing Learning Outcomes Among Senior Secondary School Students in Abuja, Nigeria
Mariana Vatamanıta	*University of European Political and Economic Science*	Tax Evasion in the Construction Sector and Its Effecta on the Public Budget
Ajayi, Osas Monday Agwu Ani Ekwe Ike Frank Chidiebere	*Federal Polytechnic Ngodo-Isuochi*	Capital Budgeting Impact on Financing Ginger and Groundnuts Seedlings Production on the Nigerian Economic Growth
Zubia Shah	*Khyber Girls Medical College*	Metabolic and Redox Adaptations to Time-Efficient Moderate Exercise in Prediabetes
Mounaim Bencheıkh Larbi El Farh	*Mohammed First University*	Tensile Strain-Induced Electronic Properties of a Thallium Selenide Monolayer: A First-Principles Study
Krishnaba Vaghela	*Gujarat Technological University*	Global Perspectives on Waste Management Practices and Policies: A Systematic Review

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27.04.2026 / ONLINE / SESSION-2 / HALL-6

Roma Local Time: 10:30-12:30 | Ankara Local Time: 11:30-13:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Nadhim M. FALEH

Authors	Affiliation	Presentation Title
S.Rubin Thara K.Vijayalakshmi N.Arshad Ahamed E.Praveena R.Swathi	*Bharath Institute of Higher Education and Research*	Digital Transformation of Pharmacy Practice
Seid Yimam Mohammed Fatmata Turay	*Woldia University*	The Paradox of Formal Education and Experiential (Tacit) Learning in Rethinking Higher Education for Sustainable Development: A Conceptual Paper Based on Multiple Theories
Nadhim M. Faleh	*Mustansiriyah University*	Social Integration: A Humanistic Vision Based on the Friday Sermons of Muhammad Al-Sadr
Addoun Rayan Ikram	*University of M'Hamed Bougara of Boumerdès*	Control and Stabilisation of Strongly Coupled Hyperbolic Systems with Kinetic Boundary Conditions and Implicit Memory Effects
Soukaina Ameur Assiya Atıf	*Chouaib Doukkali University*	DFT-Based Chemo- and Stereoselectivity Analysis of the 1,3-Dipolar Cycloaddition between 5,5-Dimethyl-3-methylenepyrrolidin-2-one and Phenyl(phenyldiazen-1-ium-1-ylidene)methanide with Docking and ADMET Evaluation
Alomgir Hossan Bibi Morium	*University of Rajshahi*	Democratic Deficit and Political Culture in Bangladesh: A Roadmap to Transparency, Accountability, and Sustainable Democratic Practices
Serghei Vasilachi Natalia Bolgari	*University Lecturer*	Digital Collaboration Tools and Student Engagement in Group Projects
Xhuljeta Meçaj	*University of Durrës*	Does Education Reduce Gender Inequality in the Labour Market? Evidence from Southeast Europe
Maribel Caicedo	*Latin American Faculty of Social Sciences*	Poverty as a Determinant of Domestic Firewood Consumption and Its Effect on the Forests of Ecuador

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27.04.2026 / ONLINE / SESSION-3 / HALL-1

Roma Local Time: 13:00-15:00 | Ankara Local Time: 14:00-16:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Fehmi Burçin ÖZSOYDAN

Authors	Affiliation	Presentation Title
Zeki Gümüşhan İsmet Kandilli	*Kocaeli University*	Analysis of Signal Strength from a Local Ads-B Receiver Station Using Artificial Neural Networks
Zeki Gümüşhan İsmet Kandilli	*Kocaeli University*	Signal Analysis of Automatic Dependent Surveillience – Broadcast (Ads-B) System
Başak Üstün Selin Yabacı Karaoğlan	*Adana Alparslan Türkeş Bilim Ve Teknoloji University*	Evaluation of the Utilization Potential of Nutrient-Rich Cold-Pressed Black Cumin (*Nigella sativa* L.) Seed Cake in Model Foods
Murat Sönmez İsmet Kandilli	*Kocaeli University*	Comparative Analysis of Machine Learning Models for Cod Prediction in Wastewater Treatment Plants
Kaan Çullu Fehmi Burçin Özsoydan	*Dokuz Eylül University*	A Reinforcement Learning Based Hyper-Heuristic Genetic Algorithm for Training Feedforward Neural Networks
Kaan Çullu Fehmi Burçin Özsoydan	*Dokuz Eylül University*	A Comparative Analysis of Network Architecture and Activation Function Choice in Feedforward Neural Networks Trained with a Hyper-Heuristic Genetic Algorithm
Zeynep Buse Karahan Reyhan Akat	*Yozgat Bozok University*	Restoration Application of the Sivas Haras Region and Its Evalution at the Urban Scale
Fehmi Burçin Özsoydan Esra Duygu Durmaz İlker Gölcük	*Dokuz Eylül University*	A Q-Learning Approach for 0-1 Knapsack Problem
Fehmi Burçin Özsoydan	*Dokuz Eylül University*	A Q-Learning Approach for Travelling Salesman Problem

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27.04.2026 / ONLINE / SESSION-3 / HALL-2

Roma Local Time: 13:00-15:00 | Ankara Local Time: 14:00-16:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Betül ÜNAL

Authors	Affiliation	Presentation Title
Betül Ünal	*Hacettepe University*	Spatial Resilience Assessment Through Modularity and Connectivity: A Design-Based Approach
Betül Ünal	*Hacettepe University*	Reframing Spatial Resilience Beyond Anthropocentrism: Material Agency Through Biodesign
Ebru Arslanhan Ayşe Çinpolat Cansu Kara Gökhan Uyanık	*Hatay Mustafa Kemal University*	Renal Damage Associated with Ovarian Remnant Syndrome (Ors) and Stump Pyometra in a Bitch
Furkan Şimşek Reyhan Akat	*Yozgat Bozok University*	Adaptive Reuse of the Sivas School of Industry Museum and the Archeology Museum
Esra Duygu Durmaz İlker Gölcük Fehmi Burçin Özsoydan	*İzmir Bakırçay University*	A Fermatean Fuzzy Ahp Approach for Prioritizing Disaster Assembly Area Selection Criteria
İlker Gölcük Fehmi Burçin Özsoydan Esra Duygu Durmaz	*İzmir Bakırçay University*	Optimization of Type-1 Fuzzy Inference System Using Metaheuristic Algorithms for Classification Problems

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27.04.2026 / ONLINE / SESSION-3 / HALL-3

Roma Local Time: 13:00-15:00 | Ankara Local Time: 14:00-16:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. Erhan KARAKAYA

Authors	Affiliation	Presentation Title
Michail Mihaylov	*Latin American Faculty of Social Sciences*	Nature, Importance and Features of the Processes in the Rivers of Bulgaria
Fatima Moutakıf Soukaına Ameur	*Chouaib Doukkali University*	1,3-Dipolar Cycloaddition of 4-Acyl-1h-Pyrrole-2,3-Diones Fused with Heterocycles and Diphenylnitrone: Insights from Medt, Docking, and Molecular Dynamics
Akbar Ali Ali Hamza Kainat Zohra	*Government College University Faisalabad*	A Reliable Method for the Selective Recognition of Lead and Mercuric Ions Using 1,2,4-Triazole Functionalized Silver Nanoparticles
Ibrahim Sani Dikko	*Umaru Musa Yar'adua University Katsina*	The Role of Biochemistry in Elucidating Human Disease Mechanisms
Mounir Boutarbouch Khadija El-Moustaqim Jamal Mabroukı	*Mohammed V University in Rabat*	Integrated Modeling and Optimization of Electrocoagulation Process for Controlled Hydrogen Generation and Efficient Treatment of Fracturing Flowback Fluid
Narmin Isalı	*Sumgayit State University Sumgayit*	Development of Measurement and Assessment Tools for Evaluating Students'; Climate Literacy in the Subject of Biology
Subhan Garagozov	*Azerbaijan University of Architecture and Construction*	Application and Prospects of Artificial Intelligence in Project Management Within the Framework of Ipma Standards
Anita Pandey	*Kirodimal Govt. Arts and Science College*	Impacts of Environmental Variables on Spider Diversity
Pooja Rasal Gaurav Kasar	*Jes's Snd College of Pharmacy*	The Role of Mtor Signaling in the Biology of Ageing

(All speakers required to be connected to the session 10 min before the session starts)
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27.04.2026 / ONLINE / SESSION-3 / HALL-4

Roma Local Time: 13:00-15:00 | Ankara Local Time: 14:00-16:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Faisal NAZIR

Authors	Affiliation	Presentation Title
Abdelaadim Khriss Aissa Kerkour Elmiad Mohammed Badaoui	*Mohammed Premier University*	Entropic Regularization as a Training Signal in Parameterized Quantum Circuits for Imbalanced Medical Classification
Piotr Salachna Maksym Hryshchenko	*West Pomeranian University of Technology in Szczecin*	Comparison of Mineral Content in Nothogenus ×Amarine Bulbs
Faisal Nazir	*The University of Agriculture*	Production and Characterization of Carbon Nanotubes from Biochar Under Microwave Irradiation
Yalpi Karthik Kalpana Nanjareddy Manoj-Kumar Arthikala	*University of Mexico*	Crk44-Mediated Signaling in *Phaseolus vulgaris*: A Molecular Switch Between Mycorrhizal Symbiosis and Pathogen-Triggered Immunity
Mariami Managadze	*Tbilisi State Medical University*	The Problem of Microplastics in Environmental Medicine
Shahidul Islam	*Barishal Textile Engineering College*	Energy-Efficient Agentic Reinforcement Learning Framework for Predictive Maintenance in Resource-Constrained Edge Environments
Saurabh Kumar Sarma	*Igno University*	An Assessment of The Human-Environment Interaction in Howly: A Study of Resource Utilization and Sustainability
Bhavana .B Deepika .R Divyadharshini.R Karthika.H Kercial Merlin.A Pradhysri.P	*R.M.K. Engineering College*	Design of an Iot-Based Smart Food Storage Monitoring System for Reducing Post-Harvest Losses

(All speakers required to be connected to the session 10 min before the session starts)
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27.04.2026 / ONLINE / SESSION-3 / HALL-5

Roma Local Time: 13:00-15:00 | Ankara Local Time: 14:00-16:00

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Nıtheesh M

Authors	Affiliation	Presentation Title
Bhavana .B Deepika .R Divyadharshini.R Karthika.H Kercial Merlin.A Pradhysri.P	*R.M.K. Engineering College*	Iot-Based Multi-Hazard Detection and Alert System for Smart Agriculture
Sanjay Kumar Pintu Das	*Sarala Birla University*	Time-Dependent Advection–Dispersion Modeling of Groundwater Contamination Dynamics
Nıtheesh M	*R.M.K. Engineering College*	Taylor's Series and Its Application in Engineering
Zineb Elaboudı Samira El Aouıdı Radouan Saadı Azzouz Benkdad Zineb El Mouridi Abdelmourhit Laıssaouı Abdelaziz Madınzı Salah Souabı	*University of Hassan Ii Casablanca*	Radionuclide Transfer from Soil to Edible Plants and Associated Radiological Risk Assessment in Semi-Arid Agroecosystems of Meknes (Morocco)
Bruno, Ibeabuchi Anwuri Ogunbayo, Oluwatoyin Glory Owurre, Isioma Mercy	*Federal College of Education (Technical) Omoku*	Entrepreneurship Education as a Tool for Biodiversity Conservation: Implications for Curriculum Reform in Tertiary Institutions in Rivers State, Nigeria
Mrajji Ouahiba Abdeslam E. L. Bouari Omar Cherkaoui	*Hassan II University of Casablanca*	Performance Assessment of Recycled Materials for Energy Efficiency and Environmental Impact
Yahaya Abubakar Aliero	*Abdullahi Fodio University of Science and Technology*	Effect of Hydrostatic Pressure on the Thermoelectric Properties of Tin Sulfur Chalcogenides: A First-Principles Investigation
Milica Ničić Svetozar Đuranović Mila Popović Dragan Đuranović Slobodan Popović	*Academy of Vocational Studies*	Establishing Internal Control in the Implementation of Procurement in Healthcare Institutions in Small Economies with the Aim of Improving Real Management
Mılıca Nıčıć Svetozar Đuranovıć Mıla Popovıć Dragan Đuranovıć Slobodan Popovıć	*Academy of Vocational Studies*	Internal Audit as a Factor for Improving Management and Work in the Real Business of Heterogeneous Healthcare Organizations

(All speakers required to be connected to the session 10 min before the session starts)
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27.04.2026 / ONLINE / SESSION-4 / HALL-1

Roma Local Time: 15:30-17:30 | Ankara Local Time: 16:30-18:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Samed ÖZDEMİR

Authors	Affiliation	Presentation Title
Yakup Kocaman	*Yozgat Bozok University*	The Effects of Cannabidiol (Cbd) in Corneal Wound Healing
Esra Altaylı Bayram Orhan Karamustafaoğlu	*Amasya University*	An Educatıonal Game Design for Teaching the Topic of Heat and Temperature
Selma Seven Çalişkan Selami Candan Nurcan Özyurt Koçakoğlu	*Gazi University*	Fine Structure of the Proboscis Sensilla in Archon Apollinus (Herbst, 1798) (Lepidoptera): A Scanning Electron Microscopy Study
Selma Seven Çalişkan Aybüke Herdi	*Gazi UniversitySamed Özdemir*	A Comparative Analysis of *Palpus labialis* Morphology in Microlepidoptera Families
Beyza Begüm Kaygusuz Yaşar Karabul Seda Erdönmez	*Yıldız Teknik University*	Gamma-Ray Shielding Performance of Polyester Composites Reınforced with Micro and Nano Sized Barium Titanate Particles

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27.04.2026 / ONLINE / SESSION-4 / HALL-2

Roma Local Time: 15:30-17:30 | Ankara Local Time: 16:30-18:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Yeasir ARAFAT

Authors	Affiliation	Presentation Title
Shreya A U Dharmananda M Harisha B S	*Nitte Meenakshi Institute of Technology*	Impact of Global Event on Stock Market Volatility: A Comparative Study of Pre-, During- and Post-Event Performance
Sanjana S Dharmananda M Harisha B S	*Nitte Meenakshi Institute of Technology*	A Study on Enhancing Service Quality at Bangalore International Airport Ltd
Jitendra Aherkar	*Atmiya University*	Social Issues Emerging Among Generation Z in Rajkot City
Rostom Ali Fakrul Islam Babul Hossain Prodhan Surovi Akther	*University of Rajshahi*	Recovery from Flood Hazards: Factors Influencing on Taking Adaptation Strategy of the Households of Post-Flood Situation in Northern Bangladesh
Yeasir Arafat	*University of Rajshahi*	Digital Connectivity and Women's Reproductive Autonomy in Bangladesh: Mediating Roles of Partner Communication and Household Decision-Making
Aqsa Kanwal Mujahad Abbas Abid Mahmood Nasir Rasool Adeel Mubarik	*Government College University Faisalabad*	Titanium-Mediated Synthesis and Pd-Catalyzed Derivatization of Thiophene Carboxylates: Antibacterial Evaluation Against Ndm-B Lactamase- Producing *Klebsiella pneumoniae* (St147)
Aliza Naeem Bushra Niaz Farhan Saeed Muhammad Afzaal	*Government College University Faisalabad*	From Biomass to Bioactivity: Global Advances in Plant Residue-Based Antioxidant and Anti-Inflammatory Therapeutics
Satish Kumar Singh	*Central University of Punjab*	Food Securıty in Armed Conflict: Revealing Gender Blınd Spots in Internatıonal Humanitarian Law
Madhura Sanap Waseem Ahmad Mir	*Jspm University Pune*	Enhancing Security in Deep Learning Systems Using Agentic AI: A Survey and Adaptive Framework

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27.04.2026 / ONLINE / SESSION-4 / HALL-3

Roma Local Time: 15:30-17:30 | Ankara Local Time: 16:30-18:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Albana HODAJ

Authors	Affiliation	Presentation Title
Mılıca Nıčıć Svetozar Đuranovıć Mıla Popovıć Dragan Đuranovıć Slobodan Popovıć	*Academy of Vocational Studies*	The Importance of Introducing a Procurement System by Establishing Control in Operation and Management of Health Institutions in Small Countries
Arjeta Hallunovi	*University Aleksander Moisiu Durres*	The Impact of Financial Mutual in the Future in Wb Countries
Le Thi Ngoc Mai	*Sai Gon University*	Mechanisms for Ensuring Legal Safety for Real Estate Buyers Through Notarization Activities in Vietnam
Iojă Anca-Emilia Habil Popescu C. Cristian	*Alexandru Ioan Cuza University*	Digitalisation, Institutions, and the Shadow Economy: Evidence from a Panel of European Union Countries
Vjollca Berisha Sevdije Govori	*University of Prishtina*	Green Microwave-Assisted, Mechanochemical, and Conventional Synthesis of Benzothiazole-Based Schiff Base Metal Complexes: Spectroscopic Characterization and Biological Activities
Monika Lopuszanska-Dawid Miroslav Kopecky	*Józef Piłsudski University of Physical Education in Warsaw*	Stress, Physical Activity, and Health Behaviors Among Adult Women
Muhammad Aminu Musa	*Kampala International University Uganda*	Evaluating the 52 Concentric Rings Ceiling as Architectural Contribution to Structural Logic, Spatial Organization, and Clan Identity in the Kasubi Tombs, Uganda
Albana Hodaj	*University Aleksandër Moisiu*	The Architecture of Exclusion in Algorithmic Societies: Rethinking Inequality and Human Cognition in the Age of Artificial Intelligence
Sayerh Fatimazahra Mouhır Latifa Saafadı Laila	*Hassan Ii University, Casablanca*	Regulation, Compliance, and Institutional Capacities in the Management of Hospital Discharges

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27.04.2026 / ONLINE / SESSION-4 / HALL-4

Roma Local Time: 15:30-17:30 | Ankara Local Time: 16:30-18:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Milea DIANA

Authors	Affiliation	Presentation Title
Aboukhalaf Abdelghani El Yacoubi Houda Anass Fellaki Rochdi Atmane	*University Ibn Tofail*	Nutritional Composition, Biological Properties, and Acute Toxicity of *Arisarum vulgare* O.Targ. Tozz: A Traditional Wild Famine Food Plant in Morocco
Anas Hamdani Abdellatif Boutagayout Atman Adiba Razouk Rachid Said Bouda	*National Agricultural Research Institute*	Towards Sustainable Water Management in Morocco: Assessing Resources, Challenges, and Adaptation Strategies
Milea DIANA	*University of European Political and Economic Science*	Criminal Aspects of Forced Marriage
Taha-Amine Miri Aissa Kerkour Elmiad Aziz Oukaira	*Mohammed Premier University*	Toward Lightweight Intrusion Detection: A Hybrid Quantum-Classical Architecture for Edge Deployment
Ndatsu, A. Fatima Isa Lawal, A. Tukur, A. Olaoye, Kaothar Opeyemi	*Federal University of Technology*	Assessment of the Progress and Challenges in Achieving Sustainable Development Goal 4 (Quality Education) at Basic Education Level in Minna Metropolis
Azhar Rishabh Malviya	*Galgotias University*	Prime Editing as a Novel Strategy to Rescue Tp53 Activity in Colorectal Cancer
Shairy Priya Rishabha Malviya	*Galgotias University*	Multifunctional Nanoplatforms for Precision Medicine: Innovations in Cancer Detection and Therapy
Madhavi Porwal Rishabha Malviya	*Galgotias University*	Breast Cancer as a Bioelectrical Disorder: Exploring the Role of Membrane Potential Dynamics and Ion Flux Signalling

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27.04.2026 / ONLINE / SESSION-4 / HALL-5

Roma Local Time: 15:30-17:30 | Ankara Local Time: 16:30-18:30

Zoom Meeting ID: 897 0755 8402 / Zoom Passcode: 123456

HEAD OF SESSION: Vasyl PUZANOV

Authors	Affiliation	Presentation Title
Gulnar Atakishiyeva Sevinç Muhtarova Shafiga İbrahimova Ayten Qajar Teymur Sadıxlı	*Baku State University*	Molecular Docking Analysis of a Dichlorodiazadiene Derivative Targeting DNA Gyrase
Gulnar Atakishiyeva Sevinc Mukhtarova Nigar Ahmedova Irada Shikhaliyeva Gulnara Babayeva	*Baku State University*	Structural Limitations of AI-Driven Drug Discovery: Bias, Reproducibility, and Risks of Predictive Interpretatio
Can. Shpat Krasniqi Ismail Mehmeti Sokol Krasniqi	*University of Applied Sciences in Ferizaj*	The Role of Transport in The Supply Chain: The Case of Kosovo in the Context of Recent Conflict Events
Vasyl Puzanov	*National University Zaporizhzhia Polytechnic*	Online Chess Hazards Within Traditional Chess Education
El Mostafa Benharaf Kaoutar Ouahibi Maryem Jemri Abdelmajid Hemmes Hamid Nasrellah Erradi EL Mostafa Abdellah Zeroual Mohammed El İdrissi	*Sultan Moulay Slimane University*	Design and Characterization of New Π-Conjugated Quinoxaline Derivatives for Solar Cells: A TD-DFT Study
Poh-Yee Loh Yong Jın Muhammad Aslam Payam Shafigh	*Universiti Malaya*	Colour Analysis of Hardened Concrete Surfaces Using Artificial Intelligence Technology
Kekeocha Mary Ezinne Ngozi Okeke	*Nnamdi Azikiwe University*	Digital Entrepreneurship Skills and Operational Efficiency of Small and Medium Scale Enterprises in Anambra State, Nigeria.
Purity Uzoamaka Ndubuisi-Okolo Grace Nwanonigwe Akaegbobi Ani Anthony Ejike Amujiogu	*Nnamdi Azikiwe University*	Digital Entrepreneurship Capabilities, Institutional Voids, and Productivity Dynamics in Small and Medium-Sized Enterprises: A Multilevel Structural Equation and Causal Mediation Analysis from an Emerging Economy Perspective
Gazi Abu Horaira Ariful Islam Sobuj Raihan	*Daffodil International University*	Impact of Workers' Remittances on Socioeconomic Development in Bangladesh: A Time-Series Analysis (1981–2025)

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CONGRESS PHOTOS













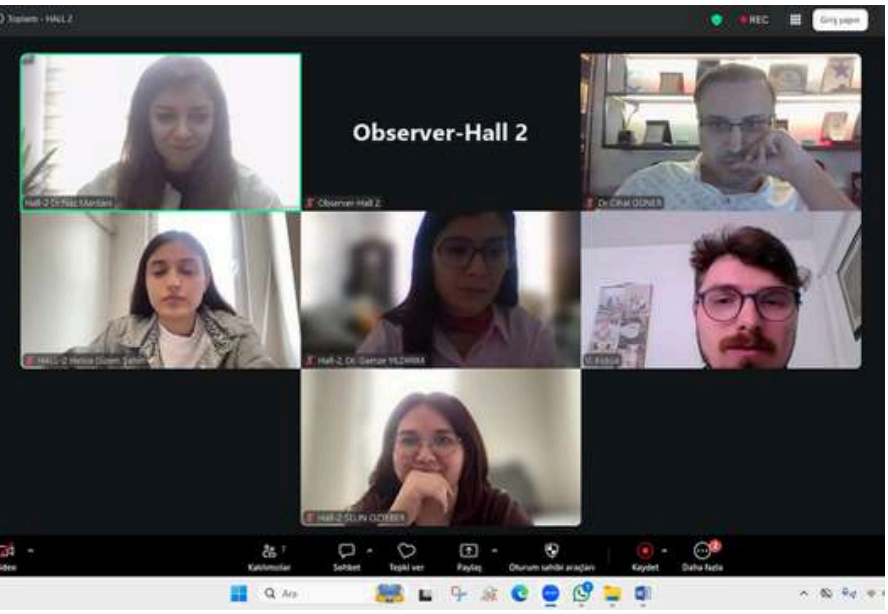
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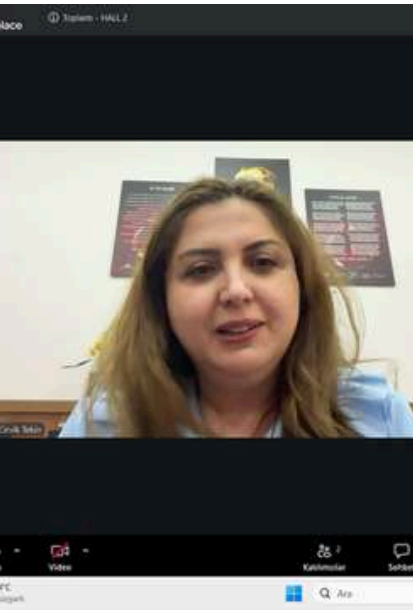
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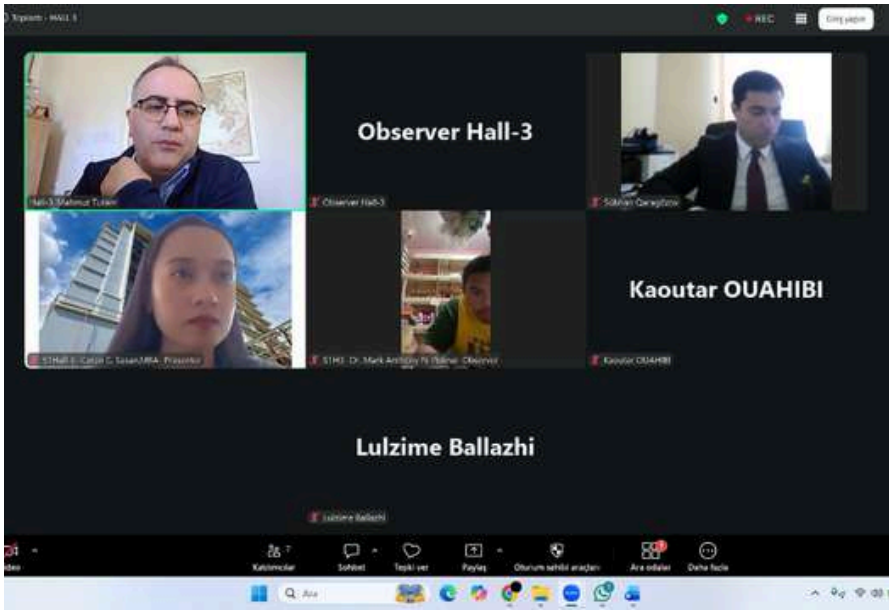


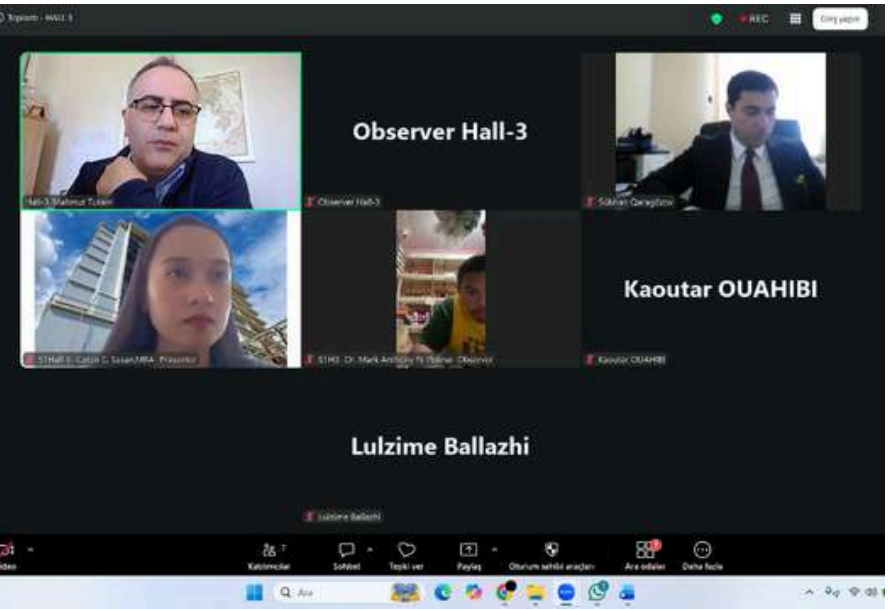
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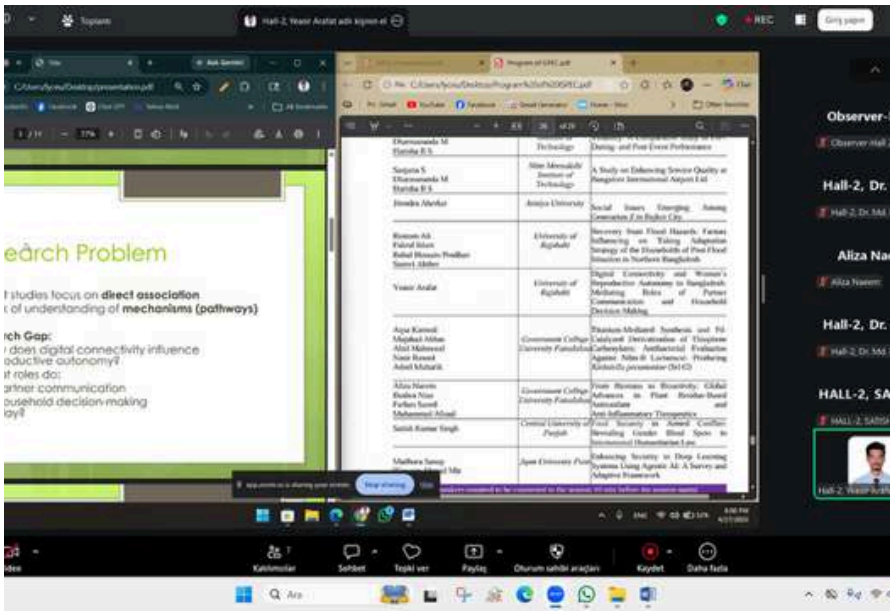




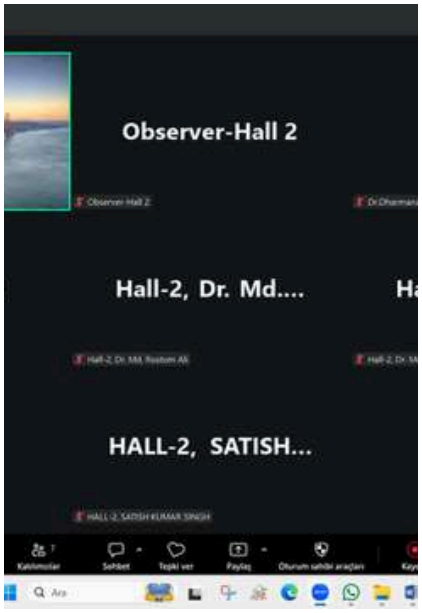


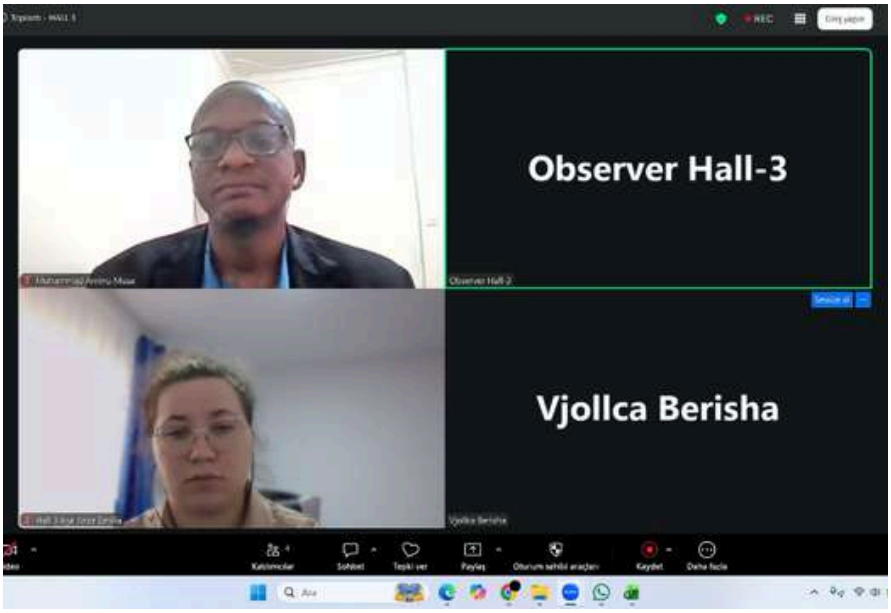


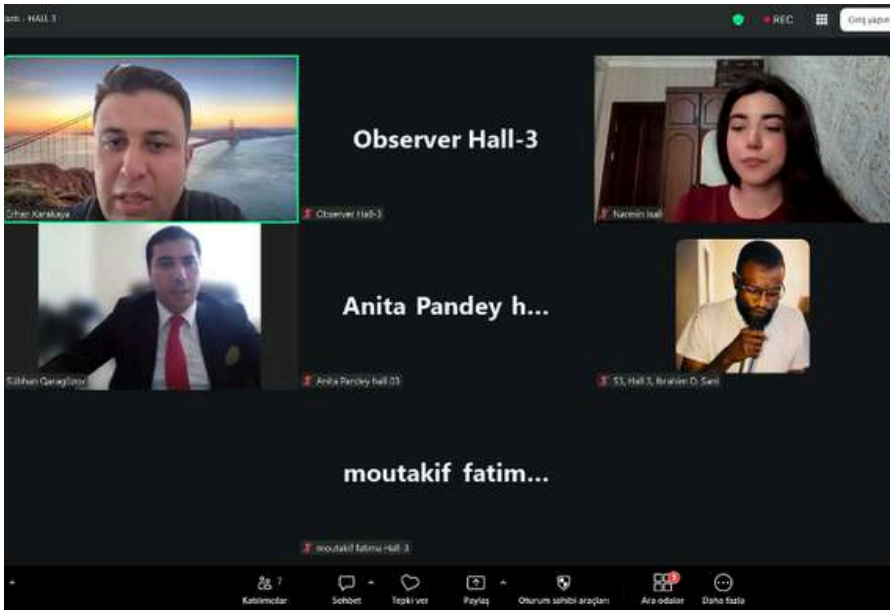
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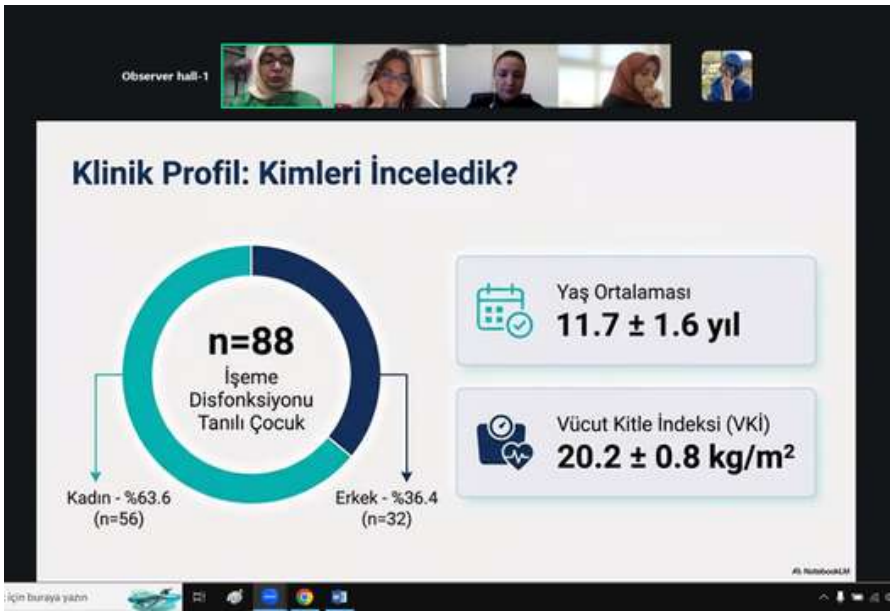


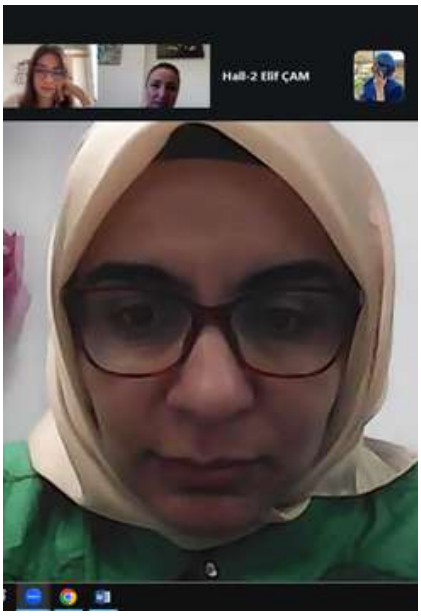


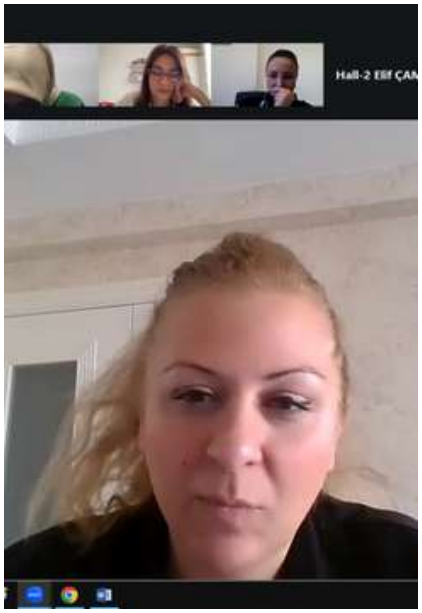


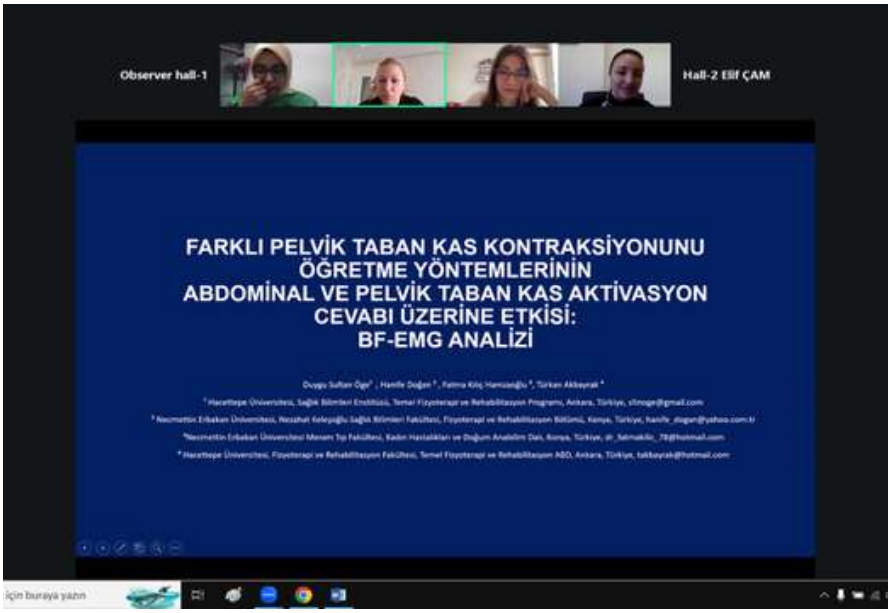


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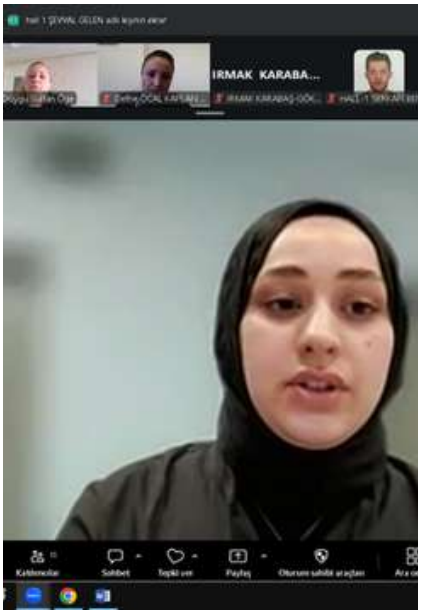




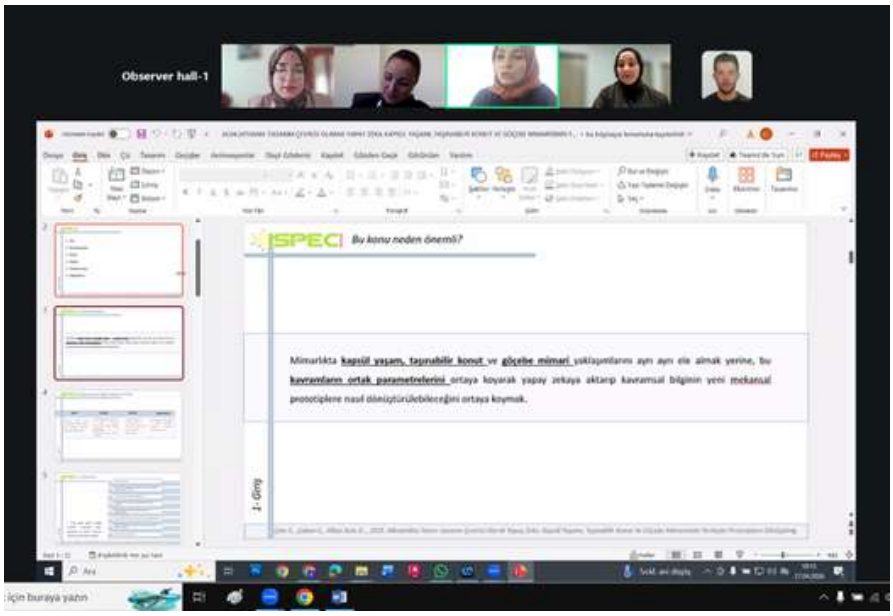


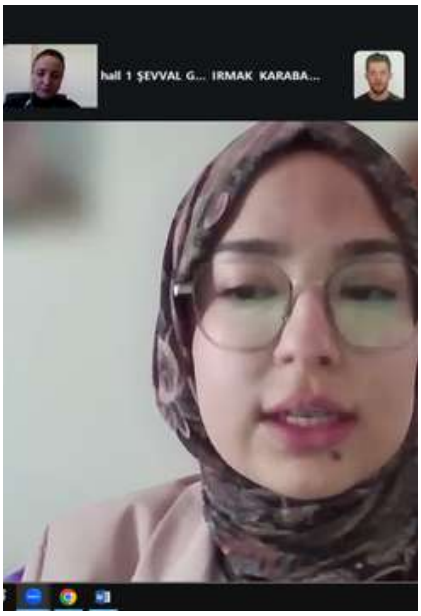


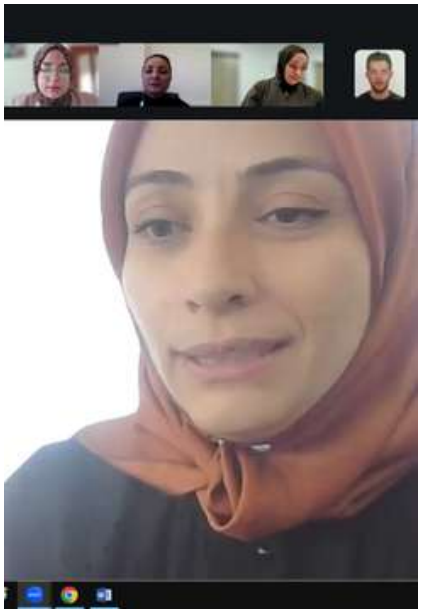


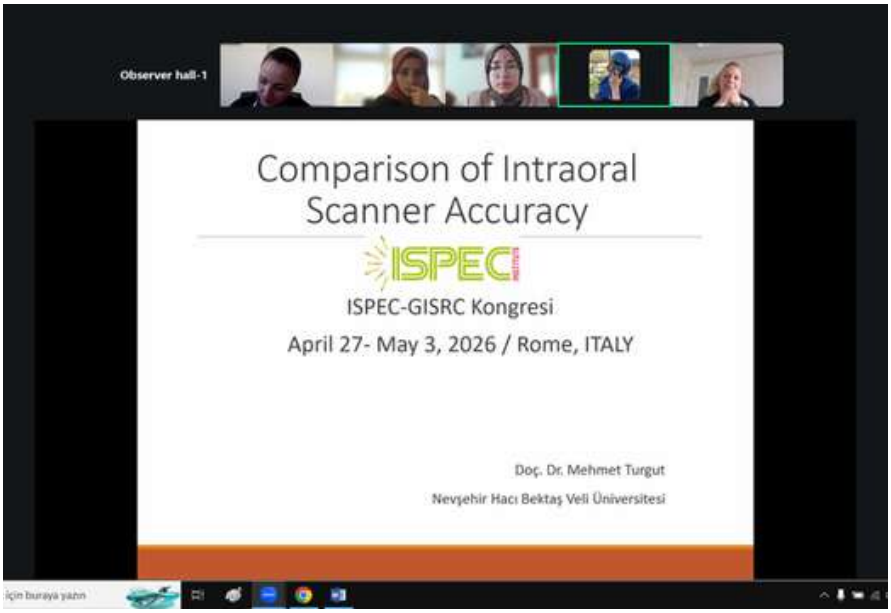


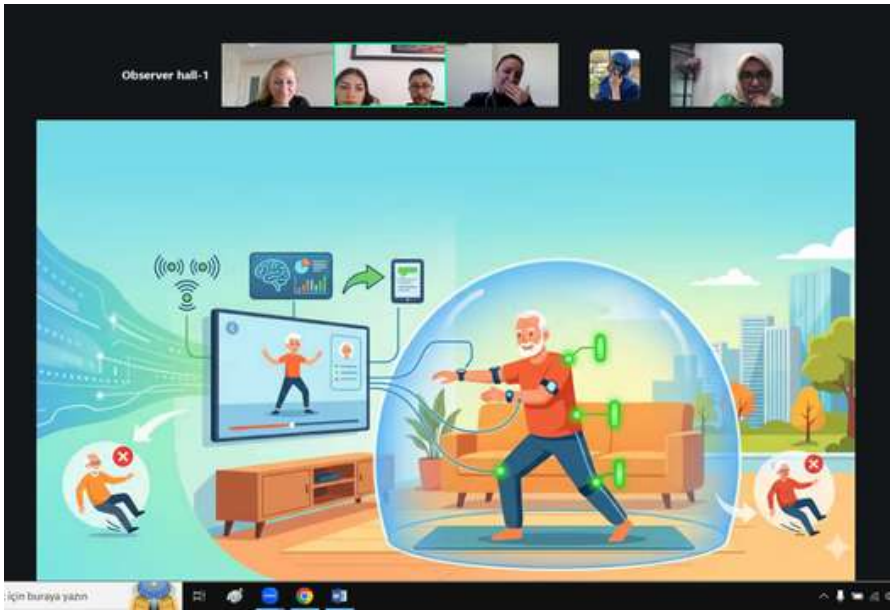
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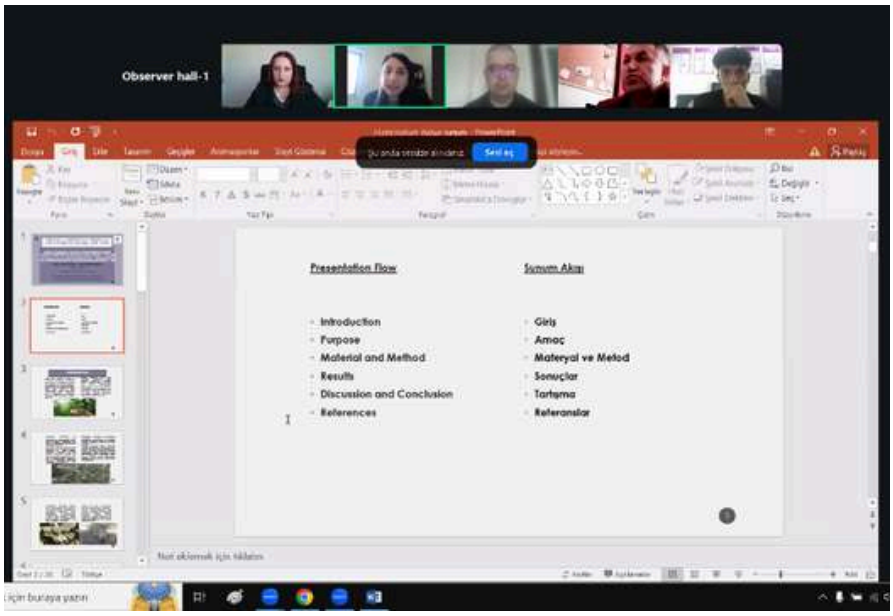


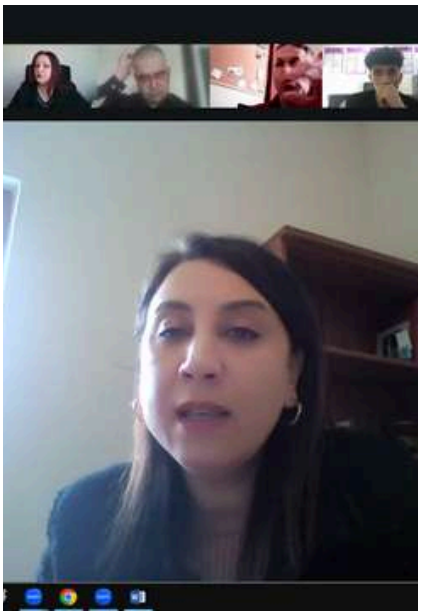


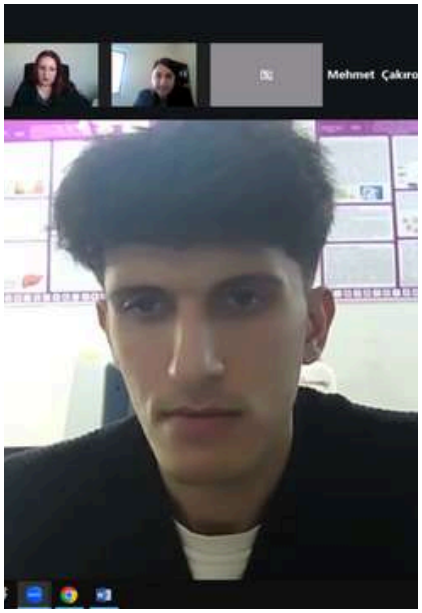


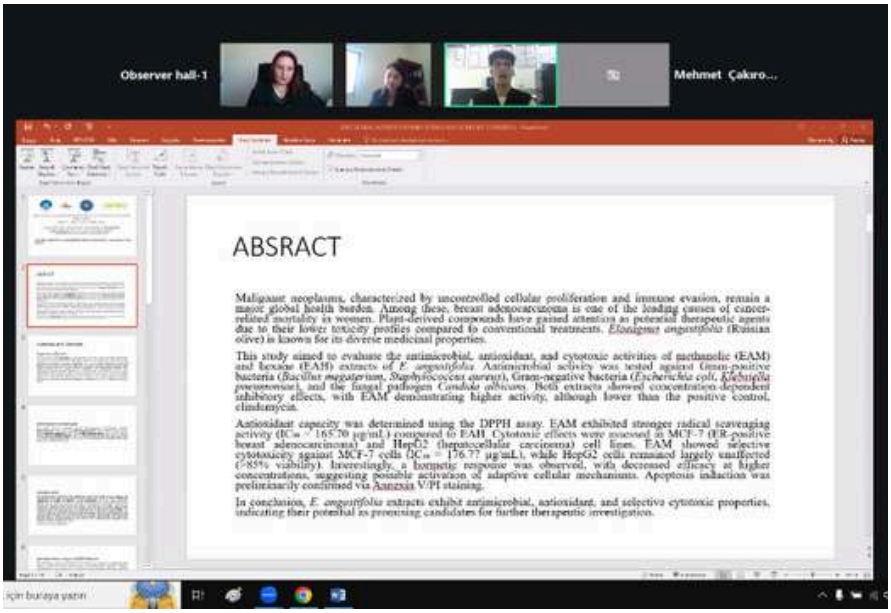


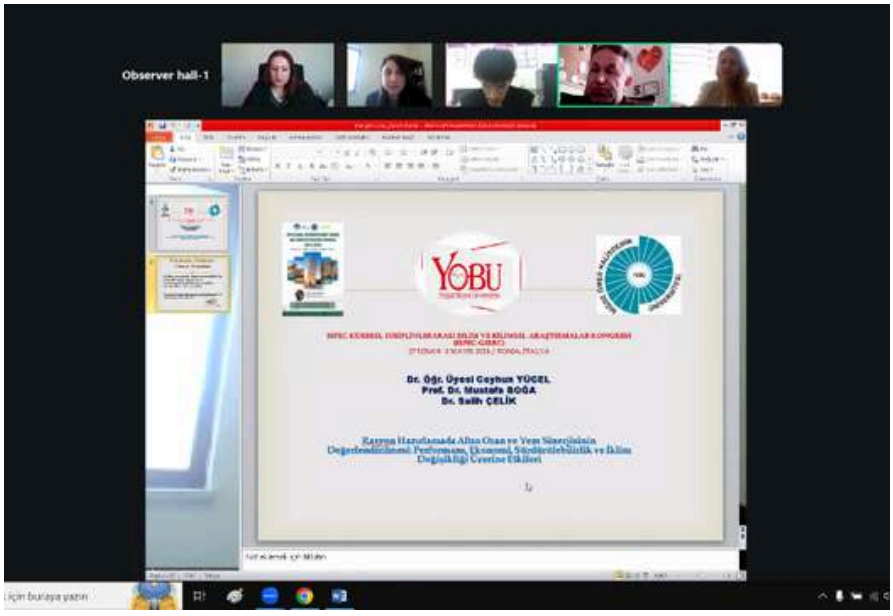
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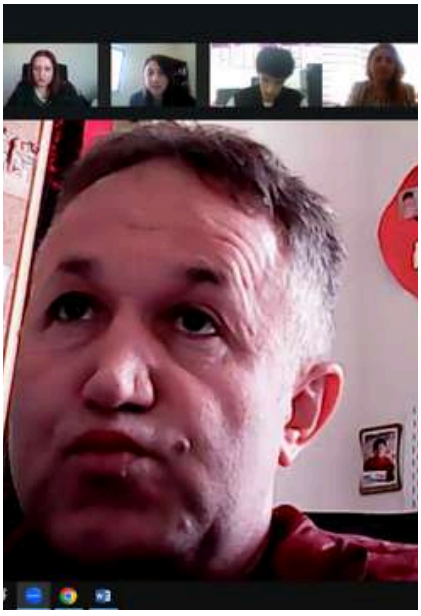




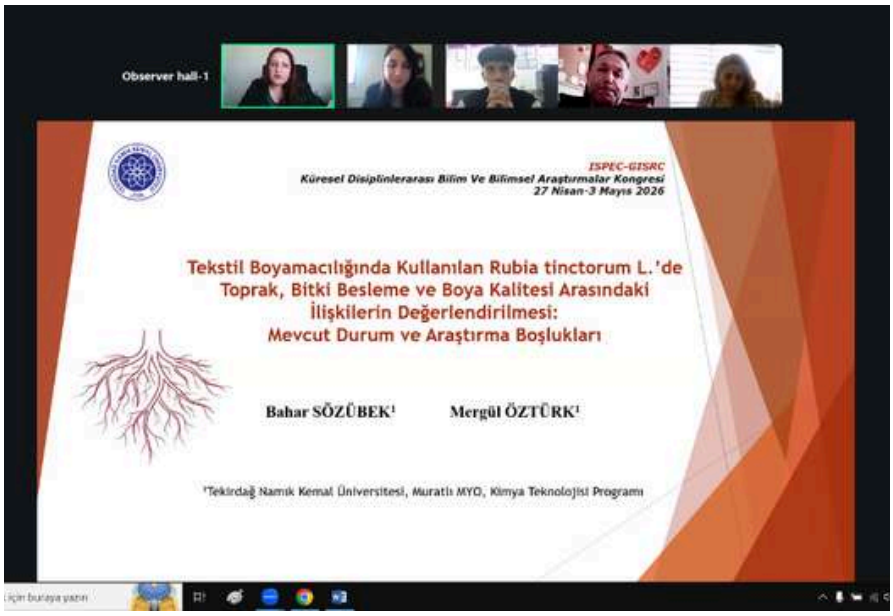


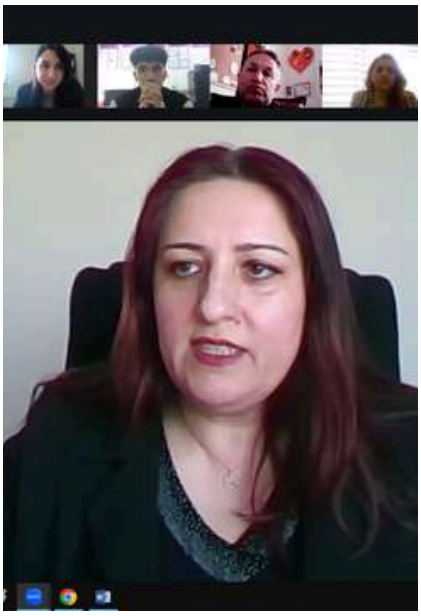


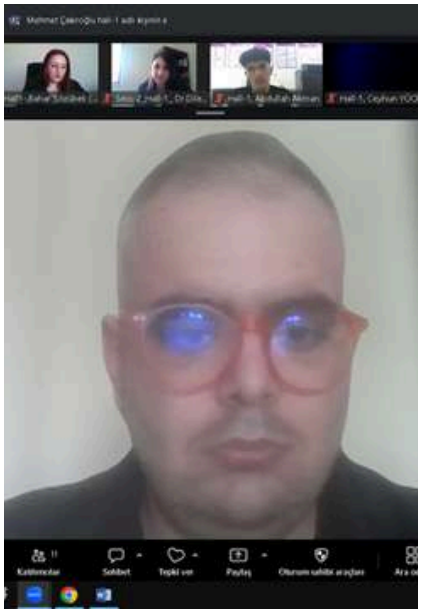


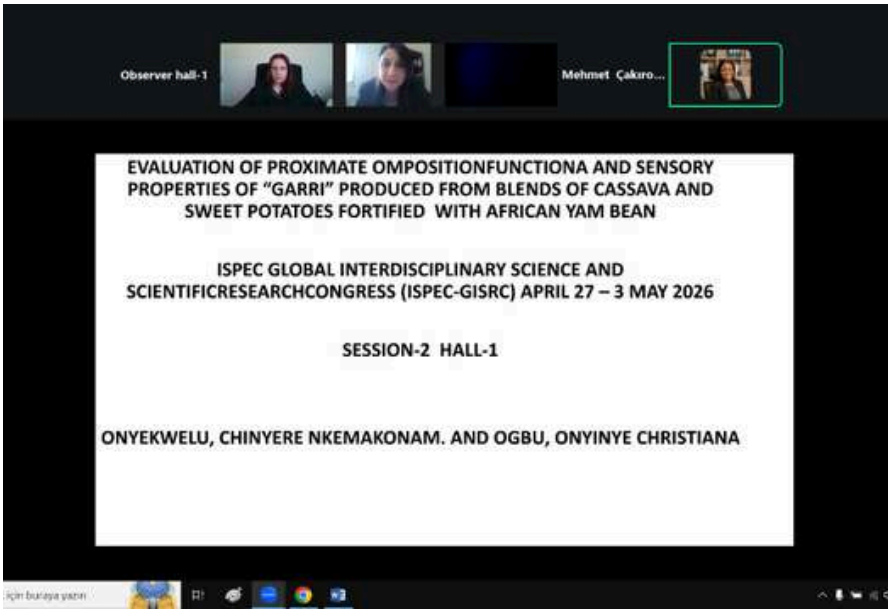


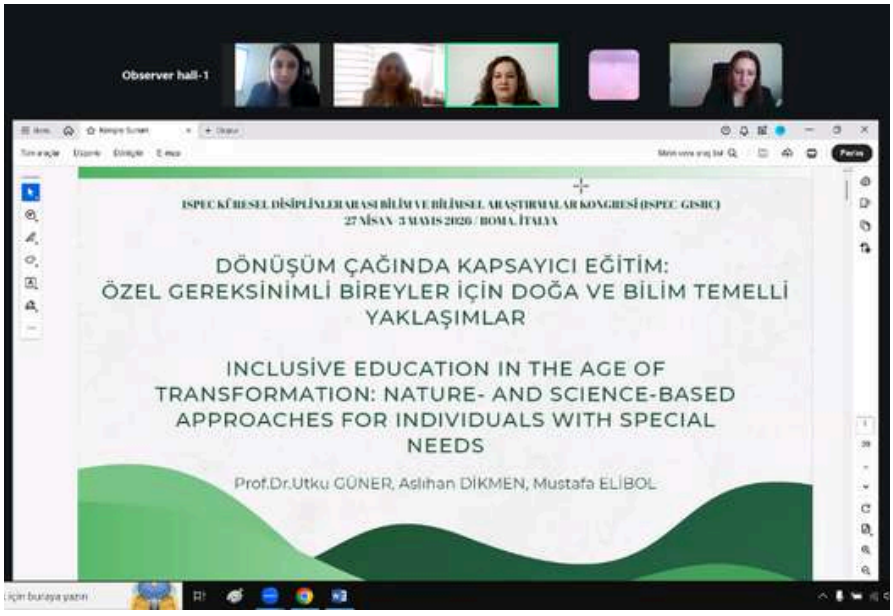
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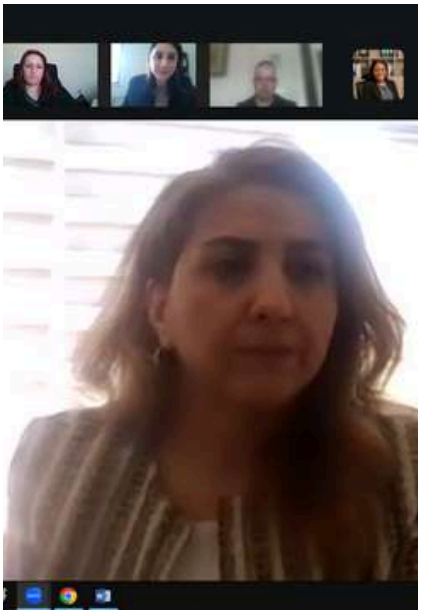




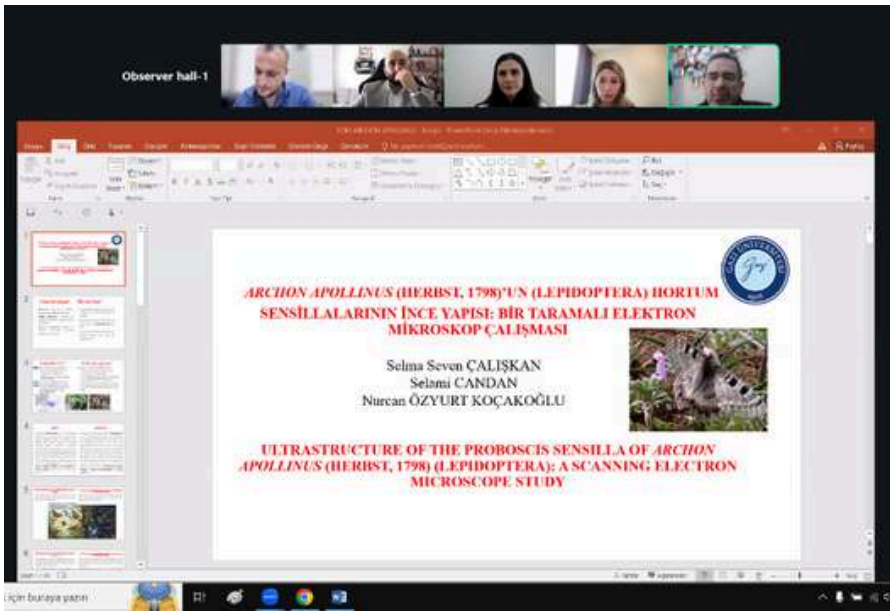


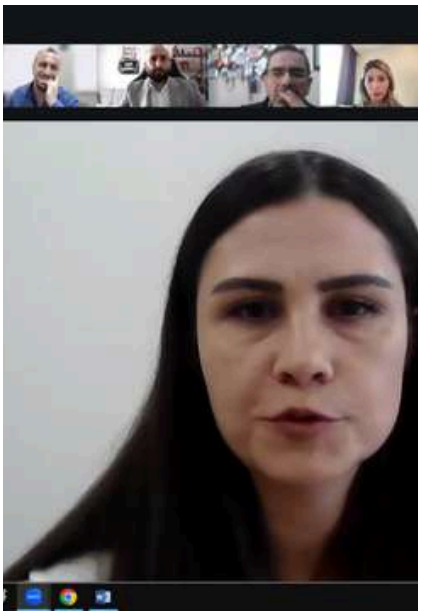


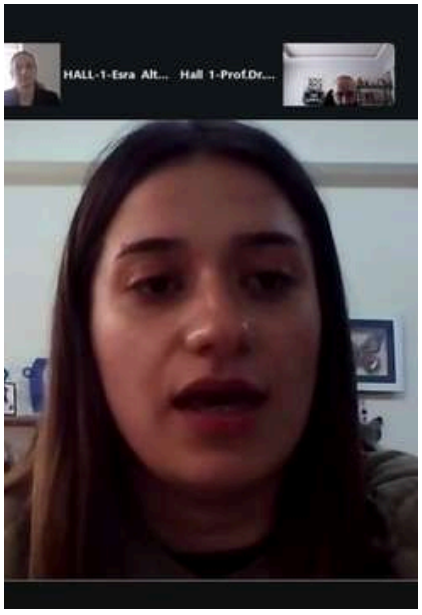


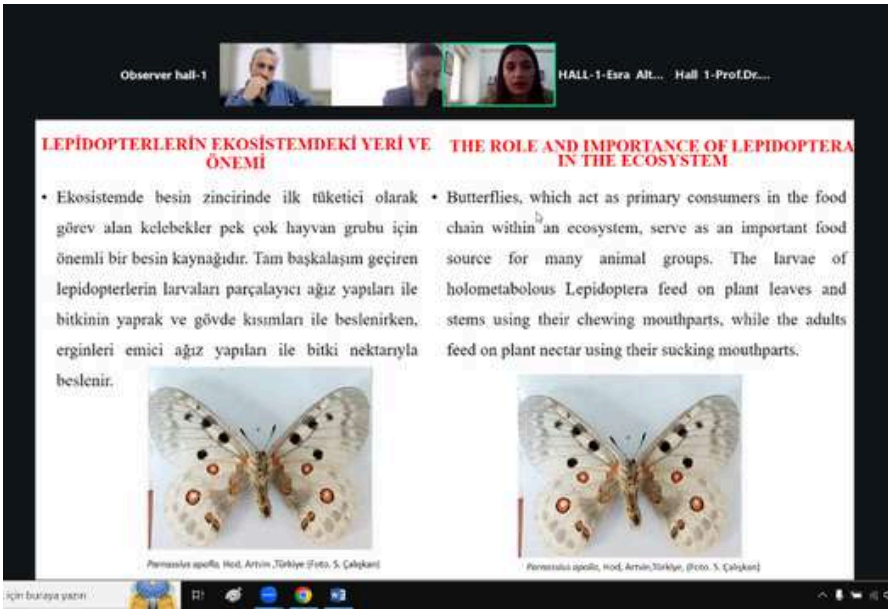


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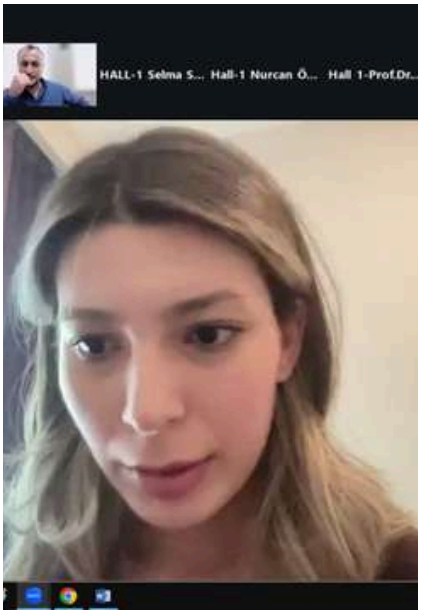












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* This study is derived from Burhan URAZ's master's thesis

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ABSTRACT



SHRİMP FOOD

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ÖZET

Kızarmış Karides; Bu karidesler bol yağda ve büyük bir kapta kızartılır. Acı salata sosu ve lezzetlendiricilerle servis edilir.

Sarımsak Tereyağ ve mısırlı karides yemeği; Bu yemek mısır, rezene ve karides içerir. Bunlar birlikte ızgarada pişirilir. Bunların yanında beyaz peynir, sıkılmış limon suyu tüketilebilir.
Hindistan cevizi karides; Bu karides Hindistan cevizi kırıntıları ile kızartılır. Daha sonra tatlı acı ve ekşi sosla servis edilir.

Defne ile marine edilmiş ve kızartılmış Karides; Karidesler limon suyu, sarımsak ve baharat çeşitleri ile marine edilir kızartılırak ve haşlanarak servis edilir.

Anahtar Kelimeler: Karides, Gastronomi, Yemek.

ABSTRACT

Air Fryer Fried Shrimp; These air-fryer shrimp are used a large pot of oil. Serve with spicy remoulade, or condiments for dipping.
Garlic Butter Shrimp and Corn; This contains corn, tomatoes, fennel and shrimp. The whole thing is broiled together. Feta, a squeeze of lemon juice are used.
Coconut Shrimp; Shrimp are coated in a light coconut breading and fried. Afterwords served with sweet chili or sweet and sour sauce.
Old Bay Marinated and Grilled Shrimp; shrimps are marinated for only 30 minutes in mix of lemon juice, garlic and spice blend, Serve with some boiled or roasted.

Keywords: Shrimp, gastronomy, Food

MİDYE YEMEKLERİ

CLAM FOOD

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ÖZET

Midye Kızartması; Midye kızartması süte bandırılır ve mısır unu ile muamele edildikten sonra kızartılır.

Midye Dolması; Midye dolması midye eti, soğan, sarımsak, ekmek kırıntıları, tereyağı, maydanoz karışımı ile yapılır. Pişirilmeden önce midye kabuğu içine doldurulur. Aynı zamanda Kırmızı ve yeşil biber, kereviz, limon suyu, acı kırmızı biber ve çok acı biber kullanılır.

Midye keki; Doğranmış midye, tereyağı, un, süt, midye suyu, yumurtanın karışımının kızartılması ile yapılır.

Midye ve pilav; Midye eti ve pilav yer fıstığı, acı biber, muz unu, kızartılmış soğan, kavrulmuş susam içerir.

Anahtar Kelimeler: Midye, Gastronomi, Yemek.

ABSTRACT

Fried Clams ; Fried Clams is served at clam shacks, fried clams are made with clams dipped in milk and corn flour, and then deep-fried.
Stuffed Clam;stuffed clam is made with a mixture of clam meat, onions, garlic, breadcrumbs or crumbled crackers, butter, and parsley. İt is stuffed into clam shells before being cooked. Red and green peppers, celery, lemon juice, paprika, red pepper, and cayenne pepper are used aswell.

Clam Cake; It is a deep-fried combination of chopped clams and batter, usually consisting of flour, milk, clam juice, eggs.

Clam Rice; Mussels and steamed rice contain peanuts, chili peppers, banana flower, fried onions, roasted sesame seeds.

Keywords: Clams , gastronomy, Food

A MULTİ-CRİTERİA MEDİTERRANEAN DİET SUSTAİNABİLİTY INDEX FOR TURKİSH HOUSEHOLDS: AN ENTROPY-TOPSIS FRAMEWORK INTEGRATİNG CARBON, NUTRİTİON, COST, AND WASTE SENSİTİVİTY

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ABSTRACT

This study develops a Multi-Criteria Mediterranean Diet Sustainability Index (MCMDSI) for Turkish households by integrating four core dimensions of dietary sustainability: carbon footprint, nutritional adequacy, affordability pressure, and waste sensitivity. Methodologically, the study employs a combined Entropy-TOPSIS framework. First, entropy weighting is used to derive objective criterion weights from the informational variability of the indicators. Second, the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is applied to rank household dietary profiles according to their relative closeness to the ideal sustainability pattern. The composite index is based on the closeness coefficient C_i where higher values indicate stronger sustainability performance.

The findings reveal that the average sustainability score is 0.512, with values ranging from 0.281 to 0.742, indicating substantial heterogeneity across household dietary profiles. The total spread of 0.461 in closeness coefficients suggests that Turkish households are distributed along a broad sustainability gradient rather than clustered around a single dietary model. Entropy results further show that the most discriminating criteria are concentrated in the cost and waste dimensions. The cost and affordability dimension accounts for 34.1% of total ranking differentiation, followed by waste sensitivity (33.4%), while nutritional adequacy (18.4%) and carbon footprint (14.1%) play comparatively smaller roles. Income-based comparisons also indicate that the largest gap between low- and high-income groups emerges in the cost sub-index, followed by waste sensitivity, suggesting that the sustainability challenge of Mediterranean-style diets in Türkiye is driven more by affordability and household food management capacity than by nutrition alone.

Overall, the study demonstrates that the Mediterranean diet should be evaluated not only as a healthy dietary model but also as a practically attainable household system. By combining objective weighting and ideal-solution ranking, the proposed MCMDSI offers a mathematically grounded and policy-relevant tool for assessing sustainable diets in Türkiye.

Keywords: Mediterranean diet, sustainable diet, Entropy, TOPSIS, household sustainability, food affordability, food waste, Türkiye

ÖZ

Bu çalışma, Türkiye'deki haneler için Akdeniz Diyeti Sürdürülebilirlik Çok Kriterli İndeksi (MCMDSI) geliştirmektedir. Önerilen indeks, diyet sürdürülebilirliğinin dört temel boyutunu birlikte ele almaktadır: karbon ayak izi, besinsel yeterlilik, satın alınabilirlik baskısı ve gıda atığı duyarlılığı. Yöntemsel olarak çalışmada birleşik bir Entropi-TOPSIS yaklaşımı kullanılmıştır. İlk aşamada, kriter ağırlıkları göstergelerin bilgi çeşitliliğine dayalı olarak entropi yöntemi ile nesnel biçimde hesaplanmıştır. İkinci aşamada ise, hane diyet profilleri TOPSIS yöntemiyle ideal sürdürülebilirlik çözümüne göre sıralanmıştır. Bileşik indeksin temel matematiksel çıktısı, C_i biçimindeki yakınlık katsayısıdır; bu katsayı yükseldikçe hane profili ideal sürdürülebilirlik yapısına yaklaşmaktadır.

Sonuçlar, ortalama sürdürülebilirlik skorunun 0.512 olduğunu, skorların 0.281 ile 0.742 arasında değiştiğini ve hane diyet profilleri arasında belirgin bir farklılaşma bulunduğunu göstermektedir. Yakınlık katsayısındaki toplam 0.461'lik fark, Türkiye'deki hanelerin tek tip bir diyet yapısında toplanmadığını, aksine geniş bir sürdürülebilirlik ekseni boyunca dağıldığını ortaya koymaktadır. Entropi bulguları, ayrıştırıcı gücü en yüksek kriterlerin özellikle maliyet ve atık duyarlılığı boyutlarında yoğunlaştığını göstermektedir. Toplam sıralama farklılaşmasının %34.1'i maliyet ve satın alınabilirlik, %33.4'ü atık duyarlılığı, %18.4'ü besinsel yeterlilik ve %14.1'i karbon ayak izi boyutundan kaynaklanmaktadır. Gelir grupları karşılaştırması da düşük ve yüksek gelir grupları arasındaki en büyük farkın maliyet alt indeksinde, ikinci olarak ise atık duyarlılığı boyutunda ortaya çıktığını göstermektedir. Bu durum, Türkiye'de Akdeniz tipi beslenmenin sürdürülebilirliğinin yalnızca sağlıklı beslenme tercihleriyle değil, esas olarak ekonomik erişilebilirlik ve hane içi gıda yönetim kapasitesi ile belirlendiğini düşündürmektedir.

Sonuç olarak çalışma, Akdeniz diyetinin yalnızca sağlıklı bir beslenme modeli olarak değil, aynı zamanda günlük yaşamda uygulanabilir bir hane sistemi olarak değerlendirilmesi gerektiğini ortaya koymaktadır. Nesnel ağırlıklandırma ve ideal çözüme yakınlık sıralamasını birleştiren önerilen MCMDSI, Türkiye'de sürdürülebilir diyetlerin ölçülmesi için hem matematiksel açıdan güçlü hem de politika yapıcılar açısından işlevsel bir araç sunmaktadır.

Anahtar Kelimeler: Akdeniz diyeti, sürdürülebilir diyet, Entropi, TOPSIS, hanehalkı sürdürülebilirliği, gıda satın alınabilirliği, gıda atığı, Türkiye

THE ROLE OF MTOR SIGNALING IN THE BIOLOGY OF AGEING

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ABSTRACT

The mechanistic target of rapamycin (mTOR) signaling pathway is a central regulator of cellular growth, metabolism, and survival, and has emerged as a key modulator of ageing and age-related diseases. mTOR integrates environmental cues such as nutrient availability, energy status, and growth factors to coordinate anabolic and catabolic processes. Dysregulation of mTOR signaling has been strongly associated with accelerated ageing and the development of chronic conditions, including neurodegeneration, cancer, and metabolic disorders.

mTOR functions through two distinct complexes, mTORC1 and mTORC2, each with unique roles in cellular physiology. mTORC1, in particular, promotes protein synthesis and inhibits autophagy, a critical cellular recycling process. During ageing, persistent activation of mTORC1 leads to reduced autophagic activity, accumulation of damaged proteins and organelles, and increased cellular stress. Conversely, inhibition of mTOR signaling, through genetic or pharmacological means such as rapamycin, has been shown to extend lifespan in multiple model organisms by enhancing autophagy and improving cellular homeostasis.

Recent research highlights the importance of balancing mTOR activity to maintain tissue function and delay ageing processes. Modulation of this pathway represents a promising therapeutic strategy for promoting healthy ageing and preventing age-associated diseases. Understanding the complex regulatory mechanisms of mTOR signaling will be crucial for developing targeted interventions aimed at extending human healthspan.

Keywords: mTOR signaling, ageing, autophagy, rapamycin, lifespan

"BİO-ORİENTED SYNTHESİS AND MOLECULAR DOCKİNG STUDİES OF 1,2,4-TRİAZOLE BASED DERİVATİVES AS POTENTİAL ANTİ-CANCER AGENTS AGAİNST HEPG2 CELL LİNE"

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ABSTRACT

Triazole-based acetamides serve as important scaffolds for various pharmacologically active drugs. In the present work, structural hybrids of 1,2,4-triazole and acetamides were furnished by chemically modifying 2-(4-isobutylphenyl) propanoic acid (1). Target compounds 7a–f were produced in considerable yields (70–76%) by coupling the triazole of compound 1 with different electrophiles under different reaction conditions. These triazole-coupled acetamide derivatives were verified by physiochemical and spectroscopic (HRMS, FTIR, ^{13}CNMR, and ^{1}HNMR,) methods. The anti-liver carcinoma effects of all of the derivatives against a HepG2 cell line were investigated. Compound 7f, with two methyl moieties at the ortho-position, exhibited the highest anti-proliferative activity among all of the compounds with an IC50 value of 16.782 g/mL. 7f, the most effective anti-cancer molecule, also had a very low toxicity of 1.190.02%. Molecular docking demonstrates that all of the compounds, especially 7f, have exhibited excellent binding affinities of 176.749 kcal/mol and 170.066 kcal/mol to c-kit tyrosine kinase and protein kinase B, respectively. Compound 7f is recognized as the most suitable drug pharmacophore for the treatment of hepatocellular carcinoma.

Key words: 2-(4-isobutylphenyl) propanoic acid; hepatocellular carcinoma; anti-cancer; 1,2,4-triazole; molecular docking; acetamides

THE PROBLEM OF MİCROPLASTİCS İN ENVİRONMENTAL MEDİCİNE

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ABSTRACT

Introduction: Microplastics represent one of the most significant challenges in modern environmental medicine due to their widespread distribution and potential adverse effects on human health. These compounds enter the environment through various routes, including marine and freshwater sources, ambient air, and food products, increasing human exposure.

The study aimed to analyze the main sources, global distribution, and pathophysiological effects of microplastics on human health based on recent scientific literature.

Study Methods and Materials: This study is based on a narrative literature review conducted in accordance with PRISMA guidelines to ensure methodological transparency and accuracy. A comprehensive search was performed in the PubMed and Google Scholar databases, covering the period from 2014 to 2024. The following keywords were used: “microplastics,” “human health,” “bioaccumulation,” “microplastics ingestion,” and “toxicology of microplastics.”

Inclusion criteria were: Peer-reviewed studies focusing on the impact of microplastics on human health, Systematic reviews, meta-analyses, original research articles. After initial screening of **134 articles**, **37** met the final eligibility criteria and were analyzed in depth.

Literature management was conducted using **Zotero**, while Microsoft Excel was used for data synthesis and thematic organization.

Results: The findings indicate that microplastics have bio accumulative properties and are linked to serious health effects, including endocrine disruption, inflammation, immune dysfunction, cancer risk, and neurodegenerative diseases.

Conclusion:
Strengthening control measures across drinking water, food, and air quality to mitigate microplastic exposure, supported by coordinated efforts in environmental regulation, public health, and education.

Key words: Microplastics, Health risks, Environmental medicine, Bioaccumulation.

TIME-DEPENDENT ADVECTION–DISPERSION MODELING OF GROUNDWATER CONTAMINATION DYNAMICS

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ABSTRACT

Groundwater contamination from agricultural runoff, industrial effluents, sewage infiltration, and geogenic processes introduces toxic pollutants such as nitrates, heavy metals, and arsenic into aquifers, posing significant risks to water quality. The transport of these contaminants in porous media is commonly described using the Advection–Diffusion Equation (ADE), though most analytical solutions assume constant flow conditions and simplified source and initial parameters, limiting their applicability in transient environments. This study develops a generalized ADE model incorporating time-dependent flow velocity, variable source concentration, and arbitrary initial conditions. An analytical solution is obtained using the Laplace transform technique, with specific cases for linear and exponential flow variations. The model is validated against numerical solutions derived from an explicit finite difference scheme, with accuracy evaluated using the root-mean-square error. The results demonstrate strong agreement and confirm the model's effectiveness in simulating transient contaminant transport, providing a reliable framework for groundwater quality assessment and management.

Keywords: Advection, *Dispersion, Variable flow velocity, RMSE*

IMPACT OF ARTIFICIAL INTELLIGENCE ON IMPROVING TEACHING PROCESSES IN HIGHER EDUCATION: A REVIEW

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ABSTRACT

Introduction
Artificial Intelligence (AI) is increasingly recognized as a transformative force in higher education, influencing the way teaching processes are planned, delivered, and evaluated. The rapid development of intelligent technologies has created new opportunities for improving teaching quality, enhancing student engagement, and supporting more personalized learning experiences. In this context, AI is being integrated into various educational practices, including adaptive learning, automated assessment, feedback generation, and learning analytics. As higher education institutions continue to adapt to technological change, it becomes important to examine how AI contributes to the improvement of teaching processes and what challenges may arise from its implementation. **The aim of this study is to examine the impact of Artificial Intelligence on improving teaching processes in higher education by analyzing the main applications, benefits, and challenges reported in the recent literature.**
Methodology
This study is based on a review of recent literature related to the use of Artificial Intelligence in higher education. Relevant academic sources were analyzed in order to identify the main applications of AI in teaching processes, as well as the benefits and challenges associated with its use. The review focuses on studies that address AI-supported teaching practices, student learning experiences, assessment methods, and institutional implementation issues.
Results
The literature indicates that Artificial Intelligence has a positive impact on improving teaching processes in higher education. AI contributes to personalized learning by adapting content and pace to students' needs, supports automated assessment and timely feedback, and assists educators in monitoring student progress and identifying learning difficulties. In addition, AI-based systems improve instructional planning and data-informed pedagogical decision-making. However, the reviewed studies also highlight several challenges, including data privacy concerns, ethical issues, lack of technological infrastructure, and limited digital preparedness among academic staff.
Conclusions
The findings suggest that Artificial Intelligence has strong potential to improve teaching processes in higher education by making them more adaptive, efficient, and responsive to student needs. At the same time, its successful integration depends on institutional readiness, clear educational policies, and a balanced approach that aligns technological innovation with pedagogical values. Therefore, AI should be considered as a supportive tool that enhances, rather than replaces, the role of educators in higher education.
Keywords: *Artificial Intelligence; higher education; teaching processes; personalized learning; educational technology*

INTEGRATED MODELING AND OPTIMIZATION OF ELECTROCOAGULATION PROCESS FOR CONTROLLED HYDROGEN GENERATION AND EFFICIENT TREATMENT OF FRACTURING FLOWBACK FLUID

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ABSTRACT

Water generated during oil and gas extraction, particularly fracturing flowback fluid (FFF), is a complex and highly polluted effluent requiring efficient and sustainable treatment solutions. Electrocoagulation (EC) has emerged as a promising technique due to its efficiency, simplicity, and low chemical consumption. However, most previous studies have focused on pollutant removal, while hydrogen (H_2) generation during EC critical for process safety and energy efficiency remains insufficiently investigated. This gap limits the safe industrial application of EC. In this work, EC combined with response surface methodology (RSM) was developed to simultaneously optimize treatment efficiency and control H_2 production during FFF treatment. A Box–Behnken design was used to evaluate the effects of electrolysis current, plate spacing, electrolysis time, and electrode surface-to-volume ratio. Here we show that removal efficiencies of turbidity and color reached 91.23% and 95.7%, respectively, under conditions minimizing H_2 production (7.86 mL), whereas higher H_2 generation (up to 138.12 mL) reduced treatment performance. Model predictions agreed with experimental results, with errors below 2.5%. These findings demonstrate that hydrogen evolution significantly influences EC performance and must be controlled for optimal operation. This study provides a reliable framework for optimizing EC processes while integrating safety considerations, enabling more efficient and scalable wastewater treatment applications.

Keywords: Electrocoagulation; Fracturing flowback fluid; Response surface methodology.

SYNTHESIS, CRYSTALLOGRAPHIC CHARACTERIZATION, AND THEORETICAL STUDY OF A NOVEL $(C_7H_8NO_2)_2H_2P_2O_7$ SINGLE CRYSTAL

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ABSTRACT

The synthesis, crystal structure determination, vibrational investigation, and theoretical analysis of the organo–mineral salt $(C_7H_8NO_2)_2H_2P_2O_7$ are presented in this work. High-quality single crystals suitable for X-ray diffraction analysis were obtained by slow evaporation at room temperature from an aqueous solution containing 2-aminobenzoic acid ($C_7H_7NO_2$) and diphosphoric acid ($H_4P_2O_7$) in a stoichiometric ratio. Single-crystal X-ray diffraction analysis indicates that the compound crystallizes in the monoclinic system with space group $P2_1/c$. The unit cell parameters are: a = 11.0657(4) Å, b = 21.2718 Å, c = 8.1544 Å, β = 105.6090°, Z = 4, and V = 1798.5(1) Å^3. The structural refinement converged to a final reliability factor R = 0.0365, confirming the accuracy and reliability of the proposed crystallographic model.The crystal structure consists of infinite one-dimensional chains of $H_2P_2O_7^{2-}$ anions interconnected via O–H···O hydrogen bonds, forming an extended supramolecular network. The organic cations $C_7H_8NO_2^+$ are located between the diphosphate chains and contribute significantly to the stabilization of the crystal packing through N–H···O and O–H···O hydrogen bonding interactions, resulting in a well-defined three-dimensional architecture. Geometrical analysis reveals the conformation of the P–O–P bridge along with distortions of the PO_4 tetrahedra. The vibrational properties were investigated by infrared and Raman spectroscopy at room temperature. The assignment of the vibrational bands was performed based on group theory and by comparison with previously reported data. Theoretical calculations were carried out using density functional theory (DFT) at the B3LYP level with the LanL2DZ basis set. Optimized geometrical parameters, harmonic vibrational frequencies, infrared intensities, Raman activities, and frontier molecular orbitals (HOMO–LUMO) were determined. The calculated results are in good agreement with the experimental findings, supporting the validity of the proposed structural model and providing further insight into the electronic distribution and the nature of the P–O–P bonding.

Keywords: Crystal structure; electronic structure, Hirshfeld, Infrared, X-ray; Computational (ELF, HSA, DFT),

METABOLİC AND REDOX ADAPTATİONS TO TİME-EFFİCİENT MODERATE EXERCİSE İN PREDİABETES

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Objectives: To determine the effect of moderate-intensity physical activity on glycaemic control and antioxidant capacity in the prediabetic population.

Methods: This experimental study was conducted in the Physiology Department of the Institute of Basic Medical Sciences at Khyber Medical University, Peshawar, Pakistan. A total of 50 adult prediabetic subjects, 22 females and 28 males, aged 18 to 35 years, were included.

The condition was diagnosed based on glycated haemoglobin levels of 5.7% to 6.4% and impaired fasting glucose (100-125 mg/dL). Anthropometric measurements and biochemical assays were performed before and after the exercise intervention. Participants engaged in moderate exercise for 30 minutes, with a maximum heart rate of 7% ± 5%, five days a week for eight weeks, monitored with a pedometer. An enzyme-linked immunosorbent assay was used to measure individual and total antioxidants.

Results: Anthropometric parameters decreased significantly after exercise. Similar changes were observed for fasting glucose ($p < 0.001$) and glycated haemoglobin ($p < 0.001$). A slight increase was noted in uric acid ($p<0.005$) and total antioxidant concentration ($p<0.001$). However, levels of superoxide dismutase, glutathione peroxidase, vitamin C, and nitric oxide decreased ($p<0.001$).

Conclusion: Moderate physical activity for 8 weeks significantly reduced individual antioxidant levels, led to a modest increase in total antioxidant capacity and uric acid, and was associated with a significant decline in anthropometric and diabetic profiles in the prediabetic population.

Keywords: anthropometry, antioxidants, physical activity, prediabetes, total antioxidant capacity

EFFECT OF RİSK COMMİTTEE INDEPENDENCE ON FİNANCİAL PERFORMANCE OF COMMERCİAL BANKS İN NİGERİA

By

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ABSTRACT

This study investigates the effect of risk committee independence on the financial performance of commercial banks in Nigeria, focusing on the period 2013–2024. Despite extensive research on corporate governance, empirical evidence on how independent risk committees influence bank profitability in emerging markets remains limited. Using a purposive sample of 11 Nigerian commercial banks, the study examines three proxies of risk committee independence: risk committee independence ratio (RCI), independent chair dummy (RIC), and CEO membership on the committee (RCE). Financial performance is proxied by return on assets (ROA) and return on equity (ROE), while bank size (logTA) and leverage (Equity/Assets) are included as control variables. Data were extracted exclusively from audited annual reports, and panel fixed-effects regression with clustered standard errors was employed. The results show that RCI and RIC have a positive and significant relationship with both ROA and ROE, while CEO membership (RCE) exhibits a weaker, but still positive, influence. The models achieved R^2 values above 0.65, and all diagnostic tests for autocorrelation, heteroskedasticity, and multicollinearity were within acceptable thresholds. Findings support agency, resource dependency, and stewardship theories, suggesting that independent risk committees enhance monitoring effectiveness and improve bank profitability. The study contributes to governance literature in emerging economies and provides practical guidance for regulators and bank boards seeking to strengthen risk oversight frameworks.

Keywords: Risk Committee Independence; Corporate Governance; ROA; ROE; Commercial Banks; Nigeria.

JEL Classification: G21; G32; G34; M48; G30; L25; D23; M12

PRİME EDİTİNG AS A NOVEL STRATEGY TO RESCUE TP53 ACTİVİTY İN COLORECTAL CANCER

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ABSTRACT

Colorectal cancer remains a leading cause of cancer-related mortality worldwide, with mutations in the TP53 gene representing one of the most critical drivers of tumor progression, therapeutic resistance, and poor prognosis. Conventional treatment strategies often fail to restore the native tumor-suppressive functions of mutant p53, highlighting the urgent need for precise genetic correction approaches. Prime editing, a next-generation CRISPR-based genome editing technology, has emerged as a versatile and highly accurate tool capable of introducing targeted insertions, deletions, and base substitutions without inducing double-strand DNA breaks. This topic will explore the molecular landscape of TP53 mutations in colorectal cancer and critically examine the potential of prime editing to correct these alterations at their genomic origin. The topic discusses the mechanistic principles of prime editing, including the role of prime editing guide RNA and reverse transcriptase, and evaluates its advantages over traditional CRISPR-Cas9 and base editing systems. Furthermore, recent preclinical studies demonstrating successful correction of TP53 mutations and restoration of p53-mediated pathways, such as apoptosis and cell cycle arrest, are analyzed. Key challenges, including delivery efficiency, off-target effects, and tumor heterogeneity, are also addressed. Overall, prime editing represents a transformative strategy with significant therapeutic promise for precision oncology, offering a novel avenue to reinstate tumor suppression in colorectal cancer.

EFFECT OF SEAWEED ENRİCHED HUMİC ACİD ON GROWTH AND YİELD OF BT. BRİNJAL (*SOLANUM MELONGENA* L.)

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ABSTRACT

Bt. brinjal (*Solanum melongena* L.), a member of the Solanaceae family, is an economically important vegetable crop cultivated worldwide across tropical, subtropical, and warm temperate regions. It has been genetically developed to resist lepidopteran pests, particularly the Brinjal Fruit and Shoot Borer (*Leucinodes orbonalis*), through the expression of *Bacillus thuringiensis* (Bt) toxin that forms pores in the insect's digestive system. In Bangladesh, where brinjal is locally known as "Begoon," it ranks second only to potato in acreage and production. The present study evaluated the effect of seaweed-enriched humic acid on the growth and yield of Bt. brinjal using a Randomized Complete Block Design (RCBD) with three replications. Four treatments were applied: T_0 (control), T_1 (recommended fertilizer), T_2 (10 kg seaweed-enriched humic acid ha^{-1}), and T_3 (20 kg seaweed-enriched humic acid ha^{-1}). Humic acid enhances nutrient availability, stimulates seed germination and viability, and primarily promotes root growth. Growth parameters—plant height, leaf number, branch number, and flower number—were recorded at 30, 50, and 80 days after sowing (DAS). The highest values were observed at DAS 80, with plant height (119 cm), leaf number (130.33), branch number (26.67), and flower number (63.35). Yield performance revealed maximum production in T_2 (21.15 ton ha^{-1}), followed by T_3 (16 ton ha^{-1}), T_1 (12 ton ha^{-1}), and minimum in T_0 (12 ton ha^{-1}). The findings indicate that seaweed-enriched humic acid significantly enhances growth and yield attributes of Bt. brinjal. Therefore, its application can be regarded as an effective, eco-friendly, and sustainable supplement to improve productivity and promote sustainable agricultural systems in Bangladesh.

Keywords : Bt brinjal, Fruit and Shoot Borer, Seaweed, Humic acid, Recommended fertilizer.

IMPACT OF WORKERS' REMİTTANCES ON SOCİOECONOMİC DEVELOPMENT İN BANGLADESH: A TİME-SERİES ANALYSİS (1981–2025)

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ABSTRACT

Workers' remittances have become one of the most important sources of foreign exchange earnings in recent years, contributing significantly to Bangladesh's socioeconomic development. Using annual time-series data from 1981 to 2025, this study examines the impact of remittances on the country's socioeconomic progress. Bangladesh remains one of the leading labour-exporting nations, with remittance inflows estimated at around USD 24–25 billion, accounting for approximately 5–6% of its GDP in 2025 (BMET, 2025). Remittance inflows continue to serve as a major source of external financing, often exceeding foreign aid and, in some cases, foreign direct investment. The findings suggest that remittances have a substantial positive impact on the economy, including poverty reduction, easing credit constraints, increasing household expenditure, boosting domestic savings, and improving access to education and healthcare. Moreover, remittances contribute to enhancing the overall quality of life and promoting gender equality. Therefore, the Government of Bangladesh needs to formulate effective and sustainable policies to maximise the developmental benefits of remittances and ensure their productive utilisation for long-term economic growth.

Keywords: Remittance, Migration, Economic Growth, Poverty-Reduction, Household Welfare, Bangladesh.

REGULATION, COMPLIANCE, AND INSTITUTIONAL CAPACITIES IN THE MANAGEMENT OF HOSPITAL DISCHARGES

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Hospital discharges constitute a source of pollution that is simultaneously organic, chemical, and microbiological, sometimes associated with pharmaceutical residues and bacteria potentially resistant to antibiotics. While technical treatment solutions are widely discussed, the actual performance of management systems also depends on institutional factors: the clarity of the regulatory framework, monitoring and enforcement capacity, coordination among stakeholders, human and financial resources, and a culture of compliance within healthcare facilities.

This study offers a social-science perspective on hospital discharge management through three dimensions: (1) regulation (standards, responsibilities, monitoring arrangements), (2) compliance (effective source-reduction practices, collection/storage, pretreatment, traceability), and (3) institutional capacities (skills, internal governance, resources, cooperation with sanitation operators and competent authorities). It draws on study findings, using physico-chemical and microbiological characterization data of effluents—including the identification of bacterial species and the analysis of antibiotic-resistance profiles—complemented by a socio-institutional analysis of management practices and compliance mechanisms. The aim is to identify the drivers and barriers to implementing requirements, as well as the gaps between formal rules and actual practice.

The approach is grounded in an analytical framework that connects risk governance with public policy implementation. It relies on a socio-institutional methodology combining documentary analysis (regulations, procedures, reports), semi-structured interviews with stakeholders (hospital management, technical services, regulatory authorities, operators), and, where possible, observation of management pathways. The expected results seek to characterize the main obstacles (fragmented responsibilities, limited resources, information asymmetries, operational priorities) and to propose improvement levers (strengthening monitoring and enforcement mechanisms, appointing a compliance focal point, training, traceability tools, contracting, and territorial coordination). By integrating synthetic risk and quality indicators (e.g., RB, risk/quality indices), the study also supports decision-making to prioritize compliance actions. By emphasizing institutional capacities, this contribution sheds light on the social and organizational conditions for more effective and responsible management of hospital discharges, with a view to protecting receiving environments and exposed populations.

Keywords: Hospital discharges; regulation; compliance; risk governance; public policy; environment; health.

"EVALUATING MYOCARDIAL PERFORMANCE AND ARTERIAL BLOCKAGES IN PATIENTS WITH A FAMILY HISTORY OF CAD"

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Introductıon
Coronary artery disease (CAD) is the leading cause of mortality worldwide. South Asia bears a disproportionately high burden of CAD, characterized by earlier onset and more severe disease. Family history is a recognized non-modifiable risk factor; however, most clinical risk models treat maternal and paternal history equally. Emerging evidence suggests maternal history may exert a stronger influence on disease severity through genetic, epigenetic, and intrauterine mechanisms. Despite these observations, data from South Asian populations remain sparse, leaving a critical knowledge gap in understanding how parental lineage shapes the clinical and angiographic profile of CAD.

Objectives: To compare the influence of maternal and paternal history of CAD on angiographic severity, left ventricular function, and clinical characteristics in patients undergoing coronary angiography.
Methods: A cross-sectional study was conducted at the Cardiology Unit of Hayatabad Medical Complex, Peshawar, involving 250 patients undergoing Coronary angiography. Data collected included demographic details, parental history of CAD, Echocardiographic parameters (LVEF, RWMA), and angiographic findings (vessel involvement, Gensini score). Patients were stratified into four groups based on family history: maternal, paternal, both, or none. Statistical analyses included ANOVA, Chi-square tests, and multivariate logistic regression.
Results: Among the participants, 25.9% had paternal history, 17.8% maternal, 9.5% both, and 46.8% no parental history. Patients with maternal history had higher mean Gensini scores (p=0.01) and lower LVEF (p=0.03). Triple-vessel disease was most prevalent among patients with a maternal history (42.5%). Multivariate regression revealed maternal history as an independent predictor of severe angiographic CAD (OR 1.58, 95% CI 1.15–2.16).
Conclusıon: Maternal history of CAD is associated with more severe coronary artery involvement and lower left ventricular function. These results underscore the need to incorporate maternal lineage into risk prediction models, prioritize early screening in these patients, and stimulate further research into the underlying biological mechanisms driving this differential risk.

Keywords: Coronary artery disease, maternal history, paternal history, Gensini score, angiography, ejection fraction

TOWARDS SUSTAİNABLE WATER MANAGEMENT İN MOROCCO : ASSESSİNG RESOURCES, CHALLENGES, AND ADAPTATİON STRATEGİES

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ABSTRACT

Water management in Morocco has become a central challenge at the intersection of climate variability, agricultural modernization, and resource governance. The country is increasingly confronted with extreme hydro-climatic conditions that threaten water security and food production. Recent years have illustrated the severity of this crisis: 2023 was the driest year in at least eight decades, with total rainfall below 100 mm and a deficit of nearly 48% compared to the national average. The six-year period from 2019 to 2024 represents the longest recorded sequence of consecutive drought years, with an average rainfall deficit of 35%. Despite a progressive increase in hydraulic infrastructure, rising from a storage capacity of 1.2 billion m3 in 1960 to more than 19 billion m3 today, reservoirs were only 28.5% full in 2024, storing 4.8 billion m3. This structural water deficit is particularly concerning given that nearly 80% of Morocco's cultivated land relies on rain-fed agriculture, making the agricultural sector vulnerable to fluctuating precipitation and rising temperatures. Morocco has attempted to address these challenges through ambitious policy frameworks, which prioritize efficient irrigation systems, sustainable agricultural practices, and resilience to climatic shocks. Largescale investments in dams, desalination, and irrigation modernization have been complemented by international partnerships that provide technical expertise and financial support to the country. Simultaneously, agroecological practices, such as agroforestry, crop diversification, and crop rotation, represent underutilized but highly relevant pathways for improving water efficiency, restoring soil fertility, reducing erosion, and enhancing biodiversity. By weaving together climatic evidence, hydrological data, and agricultural strategies, this review highlights the urgency of implementing integrated water governance in Morocco. This underscores the importance of combining technological innovation with ecological practices and policy reforms to secure water and food resources in a context marked by persistent droughts and accelerating climate change.

Keywords : Agroecological practices, Climate change, Drought, Morocco, Public policies, Integrated water resource management.

TUNING THE OPTOELECTRONIC PROPERTIES OF A–D–A BENZOTHIADIAZOLE NON-FULLERENE ACCEPTORS VIA CYANO SUBSTITUTION: A DFT/TD-DFT STUDY

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ABSTRACT

In response to the climate emergency and the growing need for efficient renewable energy sources, organic solar cells have attracted increasing attention in recent years. In this work, we present a systematic theoretical study of a series of nine non-fullerene acceptor molecules (M1–M9) designed with an **A–D–A (Acceptor–Donor–Acceptor)** architecture based on a central **benzothiadiazole (BTD)** core. In this design, the position of the electron-withdrawing **cyano (–CN)** groups is systematically varied along the planar conjugated backbone in order to evaluate its influence on the electronic and optical properties.

DFT and TD-DFT calculations were performed to investigate the frontier molecular orbitals (FMO), density of states (DOS), charge reorganization energies, molecular electrostatic potential, global reactivity parameters, and photovoltaic properties. The results reveal that the studied molecules exhibit **HOMO energy levels ranging from −5.65 to −5.28 eV** and **LUMO levels from −3.72 to −3.41 eV**, resulting in an **energy band gap (Egap) between 1.86 and 2.24 eV**. Photovoltaic calculations predict an **open-circuit voltage (Voc) of up to approximately 1.02 V** with a reference donor material. Furthermore, **TD-DFT analysis** indicates strong absorption in the visible region, with maximum absorption wavelengths ranging from **510 to 645 nm**, suggesting an efficient light-harvesting capability. These findings demonstrate favorable energy level alignment and promising optoelectronic properties, indicating that these newly designed non-fullerene acceptors could serve as promising candidates for **bulk heterojunction organic solar cells**.

Keywords: Non-fullerene acceptors (NFAs) ; Organic solar cells (OSCs) ; TD-DFT ; Optoelectronic properties ; Photovoltaic properties

FOLIAR APPLICATION OF NANO-ZINC IN VEGETABLE CROPS: MECHANISMS, EFFICIENCY, AND AGRONOMIC IMPLICATIONS

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ABSTRACT

Zinc (Zn) deficiency is a widespread nutritional constraint limiting the productivity and quality of vegetable crops worldwide. Conventional soil and foliar applications of zinc fertilizers, such as zinc sulfate, are often associated with low use efficiency due to fixation, leaching, and limited mobility within plant tissues. In recent years, nano-zinc (nano-Zn) formulations have emerged as a promising alternative, offering enhanced surface reactivity, improved penetration, and controlled release properties. This review aims to critically evaluate current knowledge on the foliar application of nano-zinc in vegetable crops, with emphasis on underlying uptake mechanisms, physiological responses, nutrient use efficiency, and agronomic performance.

The review synthesizes findings from recent experimental studies addressing leaf surface interactions, stomatal and cuticular penetration pathways, and the subsequent translocation of nano-Zn within plant tissues. Particular attention is given to the role of nano-Zn in modulating chlorophyll synthesis, photosynthetic activity, enzyme activation, and antioxidant defense systems. Evidence indicates that appropriately dosed foliar nano-Zn applications can enhance growth parameters, improve yield components, and increase the nutritional quality of vegetables, including elevated Zn biofortification levels in edible tissues.

Furthermore, this paper discusses the comparative efficiency of nano-Zn versus conventional zinc fertilizers, highlighting reduced application rates and improved nutrient use efficiency as key agronomic advantages. However, potential risks associated with over-application, nanoparticle aggregation, phytotoxicity, and environmental accumulation are also examined. The review identifies existing research gaps, including limited long-term field studies, insufficient standardization of nanoparticle characterization, and variability in crop-specific responses.

Overall, foliar nano-zinc fertilization represents a promising strategy for improving micronutrient management in vegetable production systems, provided that optimized concentrations and application protocols are established to ensure agronomic benefits while minimizing environmental and food safety concerns.

Keywords: Nano-zinc, Foliar fertilization, Vegetable crops, Nutrient use efficiency, Biofortification.

NANOTECHNOLOGY IN THE FOOD INDUSTRY: INNOVATIONS FOR SAFETY, QUALITY, AND SUSTAINABILITY

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ABSTRACT

Nanotechnology has emerged as a transformative force in the food industry, offering innovative solutions to enhance food safety, quality, and shelf life. This review provides a comprehensive overview of current applications and potential benefits in food production, processing, packaging, and preservation. By manipulating materials at the nanoscale, nanotechnology enables the development of novel food additives, sensors, and delivery systems that improve nutrient bioavailability, stability, and targeted release. Nano-encapsulation techniques allow for controlled delivery of flavors, vitamins, and preservatives, enhancing both sensory appeal and nutritional content while protecting sensitive compounds from degradation. Nanosensors embedded in packaging can continuously monitor microbial contamination, pH changes, or oxidation processes, ensuring real-time quality control and reducing food spoilage. Advances in antimicrobial nanomaterials provide effective pathogen inhibition, extending shelf life without compromising product safety or consumer acceptance. Beyond safety and quality, nanotechnology can contribute to sustainability by reducing waste, optimizing resource use, and enabling lighter, biodegradable packaging solutions. Despite these advantages, concerns related to toxicity, environmental impact, and regulatory oversight remain significant. Comprehensive risk assessments, standardized testing protocols, and clear legal frameworks are essential to maintain consumer confidence and support responsible innovation. As global food demand increases and supply chains become more complex, integrating nanotechnology offers opportunities to enhance food security, promote healthier diets, and minimize environmental footprints. Interdisciplinary collaboration among researchers, industry stakeholders, and policymakers will be crucial to realize these benefits while addressing ethical, social, and ecological considerations. Overall, nanotechnology holds considerable promise for creating smarter, safer, and more sustainable food systems worldwide.

Keywords: Nanotechnology, Food safety, Food packaging, Nutrient delivery, Food preservation.

DFT-BASED CHEMO- AND STEREOSELECTIVITY ANALYSIS OF THE 1,3-DIPOLAR CYCLOADDITION BETWEEN 5,5-DIMETHYL-3-METHYLENEPYRROLIDIN-2-ONE AND PHENYL(PHENYLDIAZEN-1-IUM-1-YLIDENE)METHANIDE WITH DOCKING AND ADMET EVALUATION

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ABSTRACT

A comprehensive theoretical investigation of the 1,3-dipolar cycloaddition between 5,5-dimethyl-3-methylenepyrrolidin-2-one (R1) and phenyl(phenyldiazen-1-ium-1-ylidene)methanide (R2) is reported. Density Functional Theory (DFT) calculations were performed to elucidate the reaction mechanism and to rationalize the observed chemo- and stereoselectivity. The results indicate a highly chemoselective process, with preferential cycloaddition at the exocyclic C=C bond of the dipolarophile. The origin of Chemo and stereoselectivity was analyzed using Frontier Molecular Orbital theory, Electron Localization Function (ELF), and Parr functions. These analyses reveal that the favored transition state is governed by optimal orbital interactions and minimized steric repulsion, leading to the exclusive formation of a single cycloadduct. Thermodynamic parameters confirm that the reaction pathway is both kinetically and thermodynamically favorable. In addition, molecular docking calculations were carried out to explore the interaction modes of the theoretically generated cycloadduct with selected protein models, providing further insight into its structural and electronic features from a computational perspective.

Keywords: 1,3-dipolar cycloaddition;ADMET; DFT ;ELF;Molecular docking; MEDT

1,3-DIPOLAR CYCLOADDITION OF 4-ACYL-1H-PYRROLE-2,3-DIONES FUSED WITH HETEROCYCLES AND DIPHENYLNITRONE: INSIGHTS FROM MEDT, DOCKING, AND MOLECULAR DYNAMICS

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ABSTRACT

A comprehensive theoretical investigation of the 1,3-dipolar cycloaddition between 5,5-dimethyl-3-methylenepyrrolidin-2-one (R1) and phenyl(phenyldiazen-1-ium-1-ylidene)methanide (R2) is reported. Density Functional Theory (DFT) calculations were performed to elucidate the reaction mechanism and to rationalize the observed chemo- and stereoselectivity. The results indicate a highly chemoselective process, with preferential cycloaddition at the exocyclic C=C bond of the dipolarophile. The origin of Chemo and stereoselectivity was analyzed using Frontier Molecular Orbital theory, Electron Localization Function (ELF), and Parr functions. These analyses reveal that the favored transition state is governed by optimal orbital interactions and minimized steric repulsion, leading to the exclusive formation of a single cycloadduct. Thermodynamic parameters confirm that the reaction pathway is both kinetically and thermodynamically favorable. In addition, molecular docking calculations were carried out to explore the interaction modes of the theoretically generated cycloadduct with selected protein models, providing further insight into its structural and electronic features from a computational perspective.

Keywords: 1,3-dipolar cycloaddition;ADMET; DFT ;ELF;Molecular docking; MEDT

EXAMPLE

THE ROLE OF TRANSPORT İN THE SUPPLY CHAİN: THE CASE OF KOSOVO İN THE CONTEXT OF RECENT CONFLİCT EVENTS

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ABSTRACT

Supply chains in small and open economies are highly vulnerable to disruptions caused by political tensions and regional conflicts. This vulnerability is particularly evident in Kosovo, a developing economy with significant dependence on imports and cross-border transport corridors. Due to its geographic position and limited domestic production, the efficiency and reliability of transport systems play a crucial role in maintaining the continuity of supply chains.

This paper examines the impact of recent conflict-related events and political uncertainties on the functioning of transport systems and supply chain performance in Kosovo. Using a qualitative analytical approach, the study relies on secondary data, institutional reports, and existing literature to identify the main challenges affecting transport and logistics operations. The focus is placed on road and cross-border transport, which represent the primary channels for goods movement in the country.

The findings highlight several key barriers, including delays at border crossings, inefficient customs procedures, infrastructural constraints, and increased logistics costs. These challenges create uncertainty in delivery times and negatively affect business operations, particularly for companies relying on time-sensitive supply chains. Additionally, disruptions in regional trade routes have forced businesses to adjust their logistics strategies, often leading to higher costs and reduced efficiency.

The study also reveals that Kosovo's reliance on a limited number of transport corridors increases its exposure to external shocks. The lack of diversification in transport routes and insufficient infrastructure reduce the system's ability to adapt to sudden disruptions. In this context, operational flexibility and the ability to respond quickly to changes become essential for maintaining supply chain resilience.

Furthermore, the paper emphasizes the importance of investing in transport infrastructure and improving regional cooperation to facilitate smoother cross-border trade. Simplifying customs procedures and enhancing coordination among regional stakeholders can significantly reduce delays and improve overall efficiency. The adoption of digital technologies, such as real-time tracking and logistics management systems, is also identified as a key factor in improving visibility and reducing risks within supply chains.

In conclusion, the case of Kosovo highlights the critical role of a resilient and adaptive transport system in ensuring supply chain stability under conditions of geopolitical uncertainty.

EXAMPLE

Strengthening infrastructure, increasing flexibility, and promoting regional integration are essential steps toward enhancing resilience and supporting sustainable economic development.

Keywords:

transport, supply chain, Kosovo, conflict, logistics, resilience, trade corridors, risk management

JEL Classification:

R40, R41, L91, F14, H54

EXAMPLE

COMPARATIVE ANALYSIS OF PRODUCTION CONSTRAINTS AMONG MALE AND FEMALE COCOYAM FARMERS IN ANAMBRA STATE

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ABSTRACT

The study assessed the constraints in small scale cocoyam production in Anambra State; gender perspective. The specific objectives of the study were to: examine the socio-economic factors affecting cocoyam production, examine the cost and returns from cocoyam production; examine the constraints faced by small scale cocoyam farmers across gender. The study was carried out in Anambra State, Nigeria. Five LGAs were purposively selected, 5 males and 5 females were randomly selected to give a total of 100 respondents for the study. Questionnaires were used to elicit information from the respondents. Data were analyzed using gross margin, linear regression and 4-point Likert Scale. Results of the study showed that cost and return structure of the small-scale cocoyam farm, provided insights into the profitability and economic feasibility of cocoyam cultivation. The total variable cost, which comprised planting, fertilizer, harvesting, clearing, ploughing/ridging, and weeding costs, amounted to ₦104,021 per hectare. The output per hectare was recorded at 2,817 kilograms of cocoyam. With an average selling price of ₦800 per kilogram, the total revenue from the farm was estimated at ₦2,253,600 per hectare and gross margin of ₦2,045,558 per hectare. The socio economic factors affecting cocoyam production were annual income and gender. Major constraints affecting small scale cocoyam farmers especially the female farmers in this study area included limited access to financial resources, lack of quality planting materials, poor market access, pest and disease infestation, accessing lands, climate change, poor soil fertility. In conclusion, this research underscores the pressing need for financial institutions to provide easy access of formal credit to small-scale female cocoyam farmers thereby reducing the constraints that hinders high productivity through the use of quality planting materials.

Keywords: Gender, constraints, cocoyam, production, comparative analysis.

EXAMPLE

ASSESSMENT OF CHALLENGES OF PROCRASTINATION BEHAVIOUR AND COUNSELLING STRATEGIES AMONG SECONDARY SCHOOL STUDENTS IN NIGER STATE, NIGERIA

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ABSTRACT

Procrastination behaviour remains a common academic challenge among secondary school students and has continued to attract attention due to its negative implications for learning outcomes. This paper assessed the nature of procrastination behaviour among secondary school students in Niger State, Nigeria, with particular focus on its prevalence, contributing factors, and the counselling strategies used to address it. Drawing from established psychological and educational theories, the paper examined internal and external factors that predispose students to procrastination, including poor self-regulation, fear of failure, peer influence, and excessive engagement with digital media. The paper also reviewed relevant counselling approaches, such as cognitive behavioural therapy, self-regulation training, motivational interviewing, and mindfulness-based strategies, as effective means of reducing procrastination tendencies among students. Findings from existing literature suggest that procrastination significantly undermines students' academic engagement, task completion, and overall performance when left unaddressed. The paper therefore highlights the critical role of school counsellors in early identification, assessment, and intervention for procrastination behaviour. It concludes that structured counselling interventions, when integrated into secondary school guidance programmes, can help students develop positive study habits, improve time management skills, and enhance academic performance.

Keywords: Procrastination, Counselling Strategies, Deviant Behaviour and Secondary School Students

EXAMPLE

MEMBRANE SEPARATİON PROCESSES İN WATER AND WASTEWATER TREATMENT: TECHNOLOGİES, CHALLENGES, AND FUTURE DİRECTİONS

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ABSTRACT

As water scarcity intensifies and environmental regulations become more stringent, membrane separation processes have emerged as pivotal technologies for sustainable water and wastewater treatment. This paper provides a comprehensive overview of current membrane technologies, ranging from microfiltration to reverse osmosis, including advanced applications such as membrane distillation and selective nanofiltration. While these systems offer superior removal efficiencies for emerging contaminants and pathogens, their large-scale deployment faces persistent challenges, most notably membrane fouling and high energy consumption. This study analyzes emerging mitigation strategies, including the development of biomimetic membranes and the integration of nanomaterials to enhance permeability and selectivity. Finally, future directions are discussed, focusing on resource recovery and the shift toward "Zero Liquid Discharge" (ZLD) systems within a circular economy framework.

Keywords: Water Treatment, Membrane Separation, Fouling, Nanofiltration, Desalination, Circular Economy.

EXAMPLE

PRİNCİPLES AND APPLİCATİONS OF DENSİTY FUNCTİONAL THEORY İN INORGANİC CHEMİSTRY: KEY CHALLENGES AND SOLUTİONS

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ABSTRACT

Density Functional Theory (DFT) has emerged as an indispensable tool in inorganic chemistry, enabling the modeling of complex systems ranging from transition metal complexes to functional nanomaterials. This presentation explores the fundamental principles governing DFT applications in the field, highlighting its critical role in deciphering electronic structures and chemical reactivity. Despite its widespread success, DFT faces persistent challenges in inorganic chemistry, particularly regarding electron self-interaction errors, the description of excited states, and the treatment of strongly correlated (open-shell) systems. This session will review recent methodological advancements designed to address these hurdles, such as the implementation of hybrid functionals, the integration of dispersion corrections (DFT-D), and the DFT+U approach. Through a series of representative case studies, we will demonstrate how these strategies allow for the accurate prediction of magnetic properties, spectroscopic signatures, and catalytic mechanisms. The objective is to provide researchers with a robust framework for selecting the most appropriate computational protocols for the specific complexities of heavy metals and d-valence shells.

Keywords: DFT, Inorganic Chemistry, Transition Metals, Electronic Structure, Electron Correlation, Catalysis.

EXAMPLE

PERCEIVED IMPACT OF TEACHER'S BEHAVIOUR ON STUDENT'S LEARNING

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Dr Yasira Waqar

Dr Afshan Naseem

Dr Aisha Sami

Dr Alams Shoaib

Dr Farhat Munir

Dr Sajid Masood

Dr Amna Yousaf

Dr Aqila Rafiq

Dr Faisal Anees

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The present study finds teachers perceptions about the impact of instructional, organizational, negative and socio-emotional behaviour of the teachers on students' learning. Further it compares perceived impact on the basis of sector, gender, teaching level and locality of the respondents. Research usus causal comparative research design. All the elementary teachers of District Gujrat make the population of this present study. Two hundred teachers were selected as a sample for this research study through stratified random sampling technique keeping in view sector, gender, teaching and locality. Data was collected using researcher made instrument with alpha reliability .91. Data was analysed using SPSS for descriptive and inferential statistics. Results showed significant opinion of teachers about impact of teachers behaviours on students learning.

Keywords: teachers' behavior, impact, students learning, elementary level school

EXAMPLE

MULTİFUNCTİONAL NANOPLATFORMS FOR PRECİSİON MEDİCİNE: INNOVATİONS İN CANCER DETECTİON AND THERAPY

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ABSTRACT

Oncological precision medicine requires the integration of systems that can simultaneously diagnose, deliver targeted drugs, and monitor therapeutics. The concept of multifunctional nanoplatforms has proven to be a revolutionary approach for integrating imaging, sensing, and treatment functions into a single nanoscale device. These systems, such as liposomes, polymeric nanoparticles, dendrimers and inorganic nanostructures, are designed to enhance the pharmacokinetics and tumour selectivity and reduce the systemic toxicity. Recent advances focus on stimuli-responsive formats that leverage the properties of the tumour microenvironment, including acidic pH, redox disequilibrium, and enzymatic activity, to enable controlled drug delivery. Simultaneously, the strategy of incorporating targeting ligands and biomarker-sensitive components enables early cancer detection and accurate localisation. State-of-the-art nanoplatforms enable multimodal treatments, including chemotherapy, photothermal therapy, photodynamic therapy, and immunotherapy, thereby augmenting treatment efficacy through synergistic effects. Moreover, biodistribution and treatment response can be monitored in real time by combining them with imaging methods, including MRI, fluorescence, and photoacoustic imaging. Although the preclinical results are promising, issues of large-scale manufacturing, long-term safety, regulatory acceptance, and clinical translation remain critical. In conclusion, multifunctional nanoplatforms are the future of precision oncology, with the potential to bridge the gap between the detection of early oncological issues and individualised treatment, thereby enhancing patient outcomes and treatment effectiveness.

EXAMPLE

GREEN MICROWAVE-ASSISTED, MECHANOCHEMICAL, AND CONVENTIONAL SYNTHESIS OF BENZOTHIAZOLE-BASED SCHIFF BASE METAL COMPLEXES: SPECTROSCOPIC CHARACTERIZATION AND BIOLOGICAL ACTIVITIES

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ABSTRACT

A novel benzothiazole-based Schiff base ligand was synthesized using conventional reflux, microwave-assisted, and mechanochemical (solvent-free grinding) methods in accordance with green chemistry principles. These approaches enabled a comparative evaluation of synthetic efficiency, where the microwave-assisted and mechanochemical methods demonstrated clear advantages over the conventional reflux method, including shorter reaction times, higher yields, and reduced solvent consumption. The synthesized ligand was subsequently coordinated with transition metal(II) ions to afford stable metal complexes. Structural characterization was carried out using FT-IR, NMR, mass spectrometry, and elemental (CHN) analysis. The coordination mode was confirmed by the shift of the azomethine ν(C=N) band toward lower wavenumbers, accompanied by the appearance of characteristic M–N vibrations, indicating coordination through nitrogen donor atoms and supporting predominantly octahedral geometries. Preliminary biological evaluation revealed that the metal complexes exhibit enhanced antiproliferative and antimicrobial activities compared to the free ligand.

Overall, this study highlights the synergistic integration of conventional and green synthetic strategies in the development of benzothiazole-based Schiff base metal complexes with promising potential in coordination chemistry and medicinal applications.

Keywords: Benzothiazole; Schiff base; Green chemistry; Microwave-assisted synthesis; Mechanochemical synthesis; Biological activity.

EXAMPLE

TAURİNE-MEDİATED MİTİGATİON OF ARSENİC AND MİCROPLASTİC TOXİCİTY İN BROCCOLİ VİA FUNCTİONAL AND MİCROSTRUCTURAL REPROGRAMMİNG

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ABSTRACT

The combined exposure of broccoli to arsenic (As) and polyvinyl chloride (PVC) microplastics represents an emerging concern for food safety, yet its mechanistic basis remains poorly understood. Co-occurrence of As and microplastics markedly impaired plant growth, photosynthetic efficiency, and nutrient acquisition, reflecting a systemic disruption of physiological processes. This decline was closely associated with severe oxidative stress, characterized by elevated levels of reactive oxygen species, increased membrane permeability, methylglyoxal accumulation, and intensified lipid peroxidation, as indicated by higher lipoxygenase activity and malondialdehyde content. Histochemical observations further confirmed excessive ROS accumulation and membrane damage. Additionally, combined stress induced pronounced microstructural alterations, including reduced epidermal and cortical thickness and diminished vascular development, thereby constraining functional performance.

Taurine application effectively mitigated these adverse effects by reinforcing antioxidant defense systems and restoring redox homeostasis through a shift toward reduced glutathione. It also improved osmotic balance via enhanced accumulation of compatible solutes and reduced arsenic uptake, thereby limiting oxidative injury. Furthermore, taurine stimulated endogenous nitric oxide and hydrogen sulfide signaling, whose interaction established a coordinated regulatory network that enhanced stress tolerance and maintained cellular integrity. Collectively, these findings demonstrate that taurine confers resilience against combined microplastic and arsenic stress through integrated functional, structural, and signaling adjustments in broccoli.

EXAMPLE

CONTROL AND STABILISATION OF STRONGLY COUPLED HYPERBOLIC SYSTEMS WITH KINETIC BOUNDARY CONDITIONS AND IMPLICIT MEMORY EFFECTS

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ABSTRACT

This work investigates a coupled system of hyperbolic equations with control applied to one of its components. The model incorporates kinetic boundary conditions and a memory effect that reflects the influence of past states on the present dynamics. Such systems naturally arise in various applications such as wave propagation, mechanical systems, and viscoelastic materials. Understanding the stabilization and control of coupled hyperbolic systems is essential for many engineering and physical applications. The presence of memory effects introduces ad-ditional complexity, making the analysis more challenging and more realistic. This study con-tributes to the theoretical understanding of how memory and fractional effects influence stability
and controllability.

A key feature of this work is the introduction of a memory kernel modeled as a functional involving a fractional operator of order ℓ. The amplitude ϱ of the kernel is explicitly linked to this exponent, leading to a nontrivial interaction between these parameters.

We establish that the polynomial stability of the system depends crucially on the interplay between the memory kernel, the fractional exponent ℓ, and the amplitude ϱ. Under suitable assumptions, we prove that the solutions decay at the rate

$$t^{-\frac{1-\ell}{2}},$$

confirming the optimality of the obtained decay rates.

Moreover, a detailed spectral analysis is carried out to derive asymptotic expressions for the eigenvalues, confirming the optimality of the obtained decay rates. The results demonstrate the significant role played by fractional memory effects and open new perspectives for further research in control theory and partial differential equations.

Keywords: Hyperbolic systems, stabilization, memory effects, fractional operators, polynomial decay, boundary control

EXAMPLE

TOWARD LİGHTWEİGHT INTRUSİON DETECTİON: A HYBRİD QUANTUM-CLASSİCAL ARCHİTECTURE FOR EDGE DEPLOYMENT

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ABSTRACT

The growing sophistication of cyber threats has made network intrusion detection a critical component of modern security infrastructure. While classical deep learning approaches have demonstrated strong detection performance, their high parameter counts and computational demands render them unsuitable for deployment on resource-constrained edge devices, where real-time threat detection is increasingly needed. This paper proposes a hybrid quantum-classical learning framework as a parameter-efficient alternative for network intrusion detection. By combining quantum processing with classical feature compression, the proposed model achieves a substantial reduction in model complexity without sacrificing detection capability. To ensure comprehensive and realistic evaluation, experiments are conducted on three benchmark datasets representing different attack landscapes, including legacy, modern, and large-scale traffic scenarios. The model achieves detection accuracies of 97.37%, 89.95%, and 99.57% across the three benchmarks, while using approximately 90% fewer parameters compared to a classical deep learning baseline. These results demonstrate that quantum-enhanced models are not only theoretically promising but can deliver competitive, measurable performance on real-world security tasks. This work contributes to the growing body of evidence that quantum-classical hybrid systems can serve as a viable foundation for next-generation, resource-aware intrusion detection systems.

Keywords: *Quantum Machine Learning, Network Intrusion Detection, Variational Quantum Circuits, Edge Computing Security, Parameter Efficiency*

EXAMPLE

TENSILE STRAIN-INDUCED ELECTRONIC PROPERTIES OF A THALLIUM SELENIDE MONOLAYER: A FIRST-PRINCIPLES STUDY

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ABSTRACT

Introduction and Purpose: Motivated by the enhanced electronic properties observed in strained InSe monolayers, this study aims to investigate the effect of tensile strain on the electronic properties of TlSe monolayers using first-principles calculations.

Materials and Methods: The calculations were performed within the framework of density functional theory using the full-potential linearized augmented plane-wave (FP-LAPW) method implemented in the Wien2k code. Structural, thermal, dynamical, and mechanical stability were validated through cohesive energy calculations, *ab initio* molecular dynamics (AIMD) simulations, phonon spectra, and elastic constants. The electronic structure was analyzed via band structure and orbital-resolved density of states (PDOS).

Results: The results reveal that tensile strain significantly modifies the electronic properties while preserving the semiconducting nature of the TlSe monolayer. The band gap increases from 0.947 eV at 0% strain to 1.227 eV at 8% strain. PDOS analysis shows that the valence band maximum (VBM) is predominantly composed of Se-4p orbitals, while the conduction band is mainly influenced by Tl-6p states. Under tensile strain, the Se-4p contributions in the valence band intensify and shift toward the Fermi level, whereas Tl-6p contributions in the conduction band progressively increase.

Discussion and Conclusion: These findings demonstrate that tensile strain is an effective tool for tuning the electronic properties of TlSe monolayers. The ability to modulate the band gap and orbital contributions highlights the strong potential of strain-engineered TlSe for future nanoelectronic and optoelectronic applications.

Key Words: Strain engineering; DFT; TlSe monolayer; Electronic property modulation

REPRESENTATION SYSTEMS AND THE MITIGATION OF PROBABILISTIC FALLACIES

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ABSTRACT

Conditional probability is a fundamental concept in probability theory, essential for decision-making under uncertainty and widely applied in fields such as medicine, engineering, finance, and data science. It provides a framework for updating probabilities as new information becomes available, allowing for more informed predictions and analyses. Despite its importance, conditional probability is frequently misunderstood. Its apparent simplicity often leads to misinterpretations and errors, commonly referred to as probabilistic fallacies. These fallacies, such as the fallacy of the transposed conditional, can result in significant mistakes in reasoning and decision-making. To address these misunderstandings, various representation systems may be used to facilitate the correct comprehension and application of conditional probability. Each system offers unique strengths and limitations in visualizing and solving conditional probability problems. The choice of representation often depends on the specific problem and the user's familiarity with each method. By understanding and appropriately utilizing these tools, students and practitioners can enhance their ability to solve conditional probability problems accurately, thereby reducing the occurrence of probabilistic fallacies.
In this work, we examine two such systems: Venn diagrams, and contingency tables, and analyze the advantages and disadvantages of each representation system, with a particular focus on their potential to eliminate, or at least mitigate, the probabilistic fallacies that frequently arise when solving conditional probability problems.

Keywords: conditional transposed fallacy, contingency table, probabilistic falacies, tree diagram, Venn diagram

EXAMPLE

EXPERT EXAMINATION OF LIQUID HYDROCARBON STORAGE TANK DAMAGE

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Liquid hydrocarbons storage tanks are used in various areas related to the production, processing, transportation and use of petroleum products. The main areas of their application are the oil industry, oil refineries, transport (automobile, railway, marine), gas stations, energy, chemical industry, manufacturing of building materials, waste storage, agriculture. These areas require high standards of safety, responsibility and effective management to prevent leaks and environmental pollution.

An expert study of tank damage must be carried out by all enterprises, institutions and organizations of all forms of ownership that use and operate liquid hydrocarbons storage tanks. The need for expert studies of tank damage is as follows:

- prevention of fines for environmental legislation violations;
- possibility to obtain a permit for pollutant emissions into the atmosphere for enterprises;
- inspection certificates for liquid hydrocarbons storage tanks will be requested in applying procedure for a new environmental permit, without these certificates, a new permit will not be issued;
- insurance coverage in case of tank damage;
- proper operational condition, long-term trouble-free use of the tank;
- positive image for stakeholders.

Organizations that comply with all requirements for environmental examinations have a better chance to attract investors, implement an environmental management system at the enterprise to achieve the goals of sustainable development of the company and the region as a whole, and enter the international market.

EXAMPLE

The result of technical diagnostics (expert examinations) is an expert opinion (report), which reflects information about the current technical condition of the tank, recommendations for its further operation.

The procedure to conduct technical diagnostics and expert examination of a tank involves conducting an audit of operational and technical documentation for the tank and inspecting the condition of the tank structure, visual and optical inspection of welded metal joints of the tank, measuring control of the thickness of metal structures of the tank, measuring control of the geometric shape and position of tank elements, control of welded joints of metal structures by physical methods (tightness control, ultrasonic or radio-radiographic control, capillary control), visual and measure control of the base condition, foundation and road surface.

In a full technical examination conducted, the tank should not be operated, it should be empty, degassed and cleaned. For a partial inspection, the tank should not be taken out of operation and prepared for examination.

According to some estimates of environmental damage from a liquid hydrocarbon spill, it has been established that in the second hour of the accident, environmental damage doubles compared to the first hour of liquid hydrocarbons entering the environment. Therefore, it is important to conduct timely and regular expert examinations of tank damage to prevent leaks and emergencies, respond quickly, and develop action algorithms in the event of accidental releases of liquid hydrocarbons into the environment.

Keywords: expert examination, **storage tank** damage, forensic activities, environmental legislation, environmental research.

EXAMPLE

ENVIRONMENTAL PROTECTION FROM TECHNOGENIC OBJECTS UNDER EARTHQUAKE AND EXPLOSION EFFECTS

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Preservation of ecological balance and safety of the population is becoming an integral part of society sustainable development. In the context of global climate change, increased seismic activity and the threat of terrorist acts and military influences, technogenic objects, objects of critical infrastructure, are becoming potential sources of environmental disasters.

Earthquakes can cause infrastructure destruction, which leads to pollution of air, water and soil. Explosions, in turn, can cause not only instant physical destruction, but also the possibility to spread pollution over a long distance. This threatens not only the surrounding area, but also the population health.

Thus, the development and implementation of measures to protect the environment from the likely negative consequences caused by earthquakes and explosions is becoming critically important in the context of preventing environmental disasters. A systematic approach to risk assessment, engineering solutions, and environmental monitoring can significantly reduce the likelihood of negative impacts. This, in turn, contributes not only to environmental conservation, but also to ensure human life and safety.

The aim of this paper is to study the effectiveness of tuned liquid dampers to mitigate structural vibrations under loading. The tuned liquid dampers have been considered as rigid tanks, partially filled with liquids. The tank is rigidly connected to an elastic structure. The developed numerical model incorporates the interaction between the structure and the tuned liquid damper. The structure has been assumed as a single degree of freedom system. To obtain the fundamental frequencies of tuned liquid damper, the boundary element method has been used. The novelty of the proposed method consists in analyze the mitigation of structure vibrations equipped with tuned liquid damper.

Single degree of freedom elastic system equipped with tuned liquid dampers, designed to control oscillations induced by external loads, liquid mass has been considered. The tuned liquid dampers absorbs energy by moving the liquid within the tank in opposition to the structure's response to dynamic loads. Figure 1. illustrates this concept schematically, showing the motion of the liquid relative to the structure.

EXAMPLE

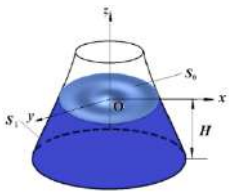


Fig. 1. Structure with Tuned Liquid Damper

A comparison of numerical and analytical results from (Raynovskyy 2020) for *l*=0 (axisymmetric modes) for different modes *k* has been provided in Table 1.

Table. 1. Axisymmetrys sloshing frequencies, Hz, L=0.

k	**Conus**
	Numerical solution
1	5.3534
2	7.8068
3	9.6034
4	11.1044
5	12.4246
6	13.6180

The results demonstrate the accuracy of the proposed numerical method.

The sloshing frequencies of conical shells have presented in Table 2.

Table 2. The sloshing frequencies of conical shells

k	**Conus**
	Numerical solution
1	5.3534
2	7.8068
3	9.6034
4	11.1044
5	12.4246
6	13.6180

The results demonstrate the accuracy of the proposed numerical method. The sloshing frequencies of conical and cylindrical shells are different, but this difference decreases as the frequency number increases [1,2].

The method is based on the use of singular integral equations to find the frequencies and vibration modes of the tuned liquid damper. The effective numerical procedure is elaborated to numerical estimation for the singular integrals.

It has been established that the use of the proposed liquid damper leads to a significant reduction in the vibration amplitude of the elastic element over the entire load range examined. The liquid dampers implementation will allow the development of effective practical solutions to ensure the stability of buildings and critical infrastructure facilities and reduce environmental threats under the influence of seismic loads, military explosions, and emergencies.

Keywords: environmental protection, earthquake, explosion, tuned liquid dampers.

EXAMPLE

“DIGITAL CONNECTIVITY AND WOMEN’S REPRODUCTIVE AUTONOMY IN BANGLADESH: MEDIATING ROLES OF PARTNER COMMUNICATION AND HOUSEHOLD DECISION-MAKING”

ABSTRACT

Background: The rapid expansion of digital technologies in low- and middle-income countries has created new opportunities for women’s empowerment. However, the pathways through which digital connectivity influences women’s reproductive autonomy remain insufficiently understood. In Bangladesh, where gender norms strongly shape health decision-making, digital access may play a transformative role.

Objective: This study examines the association between women’s internet use and reproductive autonomy in Bangladesh, with a particular focus on the mediating roles of partner communication and household decision-making power.

Methods: Using nationally representative data from the Bangladesh Demographic and Health Survey (BDHS), this study applies a cross-sectional analytical design. Reproductive autonomy is operationalized through indicators of contraceptive decision-making and healthcare utilization. Internet use is treated as the primary independent variable. To disentangle direct and indirect effects, the Karlson–Holm–Breen (KHB) decomposition method is employed within a logistic regression framework. The analysis controls for socioeconomic, demographic, and regional covariates.

Results: Preliminary findings suggest that women with internet access are significantly more likely to exhibit higher reproductive autonomy compared to non-users. A substantial proportion of this relationship is mediated by increased partner communication and enhanced participation in household decision-making. Socioeconomic status further moderates these pathways, with stronger effects observed among women from higher wealth quintiles and educational backgrounds.

Conclusion: Digital connectivity plays a critical role in enhancing women’s reproductive autonomy in Bangladesh, both directly and indirectly through improved intra-household dynamics. Policies aimed at expanding equitable digital access, alongside interventions promoting gender-equitable communication, may substantially improve reproductive health outcomes.

Keywords: Digital health, Women’s autonomy, Reproductive health, KHB decomposition, Bangladesh, Public health policy

EXAMPLE

DİGİTAL MARKETİNG STRATEGİES FOR THE PROMOTİON OF GASTRONOMİC AND DANCE FESTİVALS

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ABSTRACT

This review paper explores the role of digital marketing in the promotion and visibility of gastronomic and dance festivals within the contemporary cultural and tourism landscape. With the rapid development of digital technologies and online communication channels, festivals increasingly rely on digital platforms to reach wider audiences, enhance visitor engagement, and strengthen their cultural identity. Platforms such as Instagram, TikTok, Facebook, and YouTube have become central tools in promoting festival experiences through visual storytelling, interactive content, and user-generated media.

The objective of this review is to analyze existing academic literature and industry practices related to digital marketing strategies used in gastronomic and dance festivals. Special attention is given to how digital platforms contribute to the dissemination of cultural heritage, the promotion of traditional cuisine, and the visibility of dance performances as forms of intangible cultural expression. The paper examines how online campaigns, influencer collaborations, live-streamed performances, and multimedia promotion strategies can attract both local and international audiences.

Furthermore, the review discusses the impact of digital engagement on tourism development, highlighting how digital marketing can strengthen destination branding and support cultural sustainability. By integrating gastronomy and dance into cohesive digital narratives, festival organizers can create immersive cultural experiences that resonate with global audiences while preserving local traditions.

The study adopts a qualitative review methodology, synthesizing findings from previous research in the fields of digital marketing, cultural tourism, event management, and media studies. Through the analysis of selected case studies and marketing practices, the paper identifies key trends, challenges, and opportunities associated with the digital promotion of cultural festivals.

The findings suggest that strategic use of digital platforms significantly enhances festival visibility, audience participation, and cultural exchange. Ultimately, digital marketing emerges as a crucial tool for sustaining and expanding the reach of gastronomic and dance festivals in the global cultural economy.

Keywords: Digital marketing, gastronomic festivals, dance festivals, cultural tourism, digital promotion.

EXAMPLE

MINIMIZING MATERIAL WASTE IN AUTOMOTIVE MANUFACTURING THROUGH AI-ASSISTED GENERATIVE DESIGN

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ABSTRACT

The automotive manufacturing industry today is under increasing international pressure to implement more sustainable, environmentally friendly practices at the same time increasing the quality of the vehicles in terms of performance and safety. Despite the vigorous continuous improvement, traditional engineering methodologies are grounded on westernizing, conservative, over-engineering inherently. This conventional methodology introduces a serious disparity in the precise optimization of complicated, loaded geometries, thereby resulting in the creation of a substantial amount of raw material and heightens the carbon footprint of manufacturing activities. Consequently, the proposed research seeks to isolate and test the effectiveness of AI-supported generative design (GD) models in reducing material waste subtractive in the production of functional structural auto parts. To implement this research, a machine learning-based generative design protocol was directly incorporated with an advanced finite element analysis (FEA). The methodology was aimed at redesigning three typical high assemblies with stress such as: suspension control arms, engine mount, and structural chassis bracket. AI algorithms had been implemented, with strict compliance based on high-fidelity multi-physics parameters such as crashworthiness, fatigue limits and CNC manufacturability, using topological optimization to synthesize geometries using zero-waste as raw parametric data.

The findings of empirical studies showed record efficiency gains in manufacturing. The topologies of AI obtained a mean decrease in total component mass of 32.4% achieved. Improved, most notably, this algorithmic optimization notably reduced raw aluminum as well as high-tensile steel waste at the subtractive machining stage by 28.7% compared to the baseline human-engineered models. Moreover, physical and FEA testing showed that the generative geometries were safe by proving that the ultimate strength-to-weight ratio during maximum load testing increased by 15.2%. In conclusion, incorporation of AI-assisted generative design will provide a radically new, very resilient paradigm to the auto industry, with structural integrity being solved and a sustainable manufacturing, zero-waste production paradigm, being reached.

Keywords: Generative Design, Topological Optimization, Subtractive Manufacturing Waste, Finite Element Analysis (FEA), Sustainable Automotive Engineering, Machine Learning Algorithms.

EXAMPLE

UNVEİLİNG ADAPTİVE COMPONENTS FOR ENVİRONMENTAL HETEROGENEİTY İN *IPOMOEA CARNEA* JACQ.

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ABSTRACT

Environmental heterogeneity is an important factor that affects species richness and provides conditions for adaptation of existing species. Factors affecting the diversity gradient are climatic variation, biotic interactions, territory, ambient vigor, productivity, available water resources and some other factors that direct the historical process by the evaluation of climatic history and phylogeny of niche conversation. Naturally adapted populations of *Ipomoea carnea* Jacq. were collected from various ecological regions of Punjab province to investigate their adaptive components that have been developed under heterogeneous environmental conditions. Multivariate redundancy analysis (RDA) and correlation analysis were done to evaluate the association of soil physiochemical features with different morpho-anatomical and physiological characteristics. *I. carnea* is an invasive species that can rapidly grow, spread and adapt from xerophytic to aquatic habitats. This species showed better growth and biomass production near water bodies. Additionally, it also exhibited some specific anatomical modifications such as aerenchyma formation, sclerification, xylem ray thickness, leaf thickness and large metaxylem area that enable it to survive under harsh environmental conditions. Populations from highly saline habitats showed higher value of osmolytes and ionic contents (K^+ and Ca^{2+}). Furthermore, the populations from highly saline areas also exhibited the maximum uptake of Na^+ content and the lowest uptake of K^+ and Ca^{2+} content. In conclusion, *I. carnea* showed very specific modifications in morpho-anatomical and physiological traits that reveal its ecological success from aquatic to xerophytic habitats.

EXAMPLE

FOOD SECURITY IN ARMED CONFLICT: REVEALING GENDER BLIND SPOTS IN INTERNATIONAL HUMANITARIAN LAW

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ABSTRACT

Food insecurity has surfaced as one of the most profound humanitarian ramifications of modern armed conflicts, further intensified by both intentional and unintentional disruptions to food systems, agricultural production, and the livelihoods of civilians. Although International Humanitarian Law (IHL) furnishes normative safeguards against starvation and protects objects essential for civilian survival, its seemingly impartial stipulations frequently neglect the varied experiences of populations affected by such crises. This study undertakes a critical examination of the gendered blind spots that are ingrained within IHL frameworks that govern food security in contexts of armed conflict. Utilizing a feminist legal and socio-legal methodology, the research investigates the degree to which prevailing legal standards sufficiently address the structural vulnerabilities encountered by women, especially in environments where gendered responsibilities, disparities in resource accessibility, and socio-cultural limitations exacerbate food insecurity. The study engages in a doctrinal analysis of pivotal IHL provisions, augmented by perspectives from selected regions affected by conflict, to illustrate how ostensibly equal protections can result in substantively unequal outcomes. The findings indicate that the general protections afforded by IHL against starvation and its concentration on civilian populations lack mechanisms for gender-sensitive interpretation and implementation, thereby obscuring the specific needs of women and compromising their food security. The article advocates for a reconceptualization of IHL through a gendered perspective, underscoring the necessity of integrating intersectional viewpoints into legal interpretation, policy formulation, and humanitarian practices. By bridging the divide between food security discourse and feminist critiques of international law, this study enriches the burgeoning scholarship on gender-responsive humanitarian governance and advocates for more inclusive legal frameworks capable of addressing the intricate realities of food insecurity in contexts of armed conflict.

Keywords: *Food Security, Armed Conflict, International Humanitarian Law, Gender Inequality, Feminist Legal Theory.*

EXAMPLE

PERFORMANCE ASSESSMENT OF RECYCLED MATERİALS FOR ENERGY EFFİCİENCY AND ENVİRONMENTAL IMPACT

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ABSTRACT

The building sector accounts for a significant share of global energy consumption and greenhouse gas emissions, mainly due to heating and cooling needs. Improving thermal insulation through high-performance materials is therefore a key strategy for reducing energy demand and enhancing indoor comfort. In this context, recycling natural waste resources—such as feather fibers—into insulation materials offers a promising pathway to combine circular economy principles with substantial energy and environmental benefits.

This study evaluates the thermal performance and energy-saving potential of innovative insulation materials made from natural feather fibers. An integrated experimental and numerical methodology was employed, involving the characterization of recycled feather-based nonwovens, which showed a thermal conductivity ranging from 0.031 to 0.044 W/m·K. A dynamic simulation model, developed and validated using a real-scale test cell in Casablanca, was used to assess energy savings, reductions in greenhouse gas (GHG) emissions, and improvements in thermal comfort.

The findings reveal that feather-based insulation achieves a minimum energy performance of 30 kWh/year·m², which is below the 40 kWh/year·m² threshold required by Moroccan thermal regulations for the Casablanca climate zone. Moreover, depending on the configuration tested, GHG emission reductions reached up to 48.58%.

Keywords: Building sector, Recycled feathers, Insulation materials, Energy savings.

EXAMPLE

FROM BIOMASS TO BIOACTIVITY: GLOBAL ADVANCES IN PLANT RESIDUE-BASED ANTIOXIDANT AND ANTI-INFLAMMATORY THERAPEUTICS

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ABSTRACT

Due to increased global focus on sustainable methods of delivering healthcare services, there is a heightened interest in natural plant-based products that include the often ignored plant residue, which results from agriculture or the food industry. This research focuses on using plant biomass to create compounds that are active against oxidation and inflammation, presenting the plant residue as an important new area of green medicine. Fruit peels, seed kernels, husks, and leaves of plants contain a wide variety of phytochemicals such as polyphenols, flavonoids, and tannins, which have strong therapeutic values. The developments of new technologies, such as the use of green solvents and biotechnology, have helped to increase efficiency in obtaining and improving the effectiveness of these compounds. The paper examines developments across the globe concerning the identification and analysis of bioactive constituents of plant residues and assesses their effectiveness in tackling oxidative stress and inflammation, which are among major causes of conditions such as cardiovascular disease, diabetes, and cancer. Issues related to standardization, scalability, and regulatory clearance has also been considered to ensure a holistic understanding of the future applications. Through the intersection of waste management and medicinal development, the study demonstrates the utility of plant waste as low-cost and environmentally friendly options to artificial medications. The implications of this study call for greater cooperation between different fields and increased funding for green medication studies around the world.

Key Words: Plant Residues, Antioxidant Activity, Anti-Inflammatory Therapeutics, Phytochemicals Circular Bioeconomy

EXAMPLE

NUTRITIONAL COMPOSITION, BIOLOGICAL PROPERTIES, AND ACUTE TOXICITY OF *ARISARUM VULGARE* O. TARG. TOZZ: A TRADITIONAL WILD FAMINE FOOD PLANT IN MOROCCO.

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ABSTRACT

During famine periods in Morocco, Arisarum vulgare was traditionally consumed in rural areas and contributed to population survival. Despite its historical importance, limited research exists on its nutritional composition, bioactive properties and safety. The current study aimed to evaluate the proximate and mineral compositions, phytochemical profile and acute toxicity of A. vulgare tubers. Nutritional composition was determined using standard food analysis methods, whereas polyphenol and flavonoid contents and antioxidant activity were assessed using colorimetric assays. Antimicrobial activity was evaluated by disc diffusion and broth microdilution methods, and safety was assessed by performing acute toxicity. The finding revealed that this plant is rich in carbohydrates but low in protein and fat, while mineral and phenolic contents were at moderate levels. Biological evaluation of the extracts showed remarkable antioxidant activity and wide antibacterial and antifungal effects. The aqueous extract obtained by traditional decoction showed no acute toxicity with LD50 higher than 5000 mg/kg, which suggests that the traditional preparation method plays an important role in reducing the toxicity of A. vulgare. The results highlight the nutritional value of A. vulgare tubers and their content in bioactive compounds showing antioxidant and antimicrobial activities.

Keywords: *Arisarum vulgare*, famine food, nutritional profile, antioxidant activity, antimicrobial activity, toxicity.

EXAMPLE

RETHİNKİNG CO-CREATİON İN THE AGE OF ARTİFİCİAL INTELLİGENCE

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ABSTRACT

The concept of co-creation has traditionally been grounded in human-centered interactions, where value emerges through collaboration between firms, institutions, and stakeholders. However, the rapid advancement of artificial intelligence, particularly generative AI, challenges this foundational premise by introducing non-human agents into the co-creation process. This paper proposes a reconceptualization of co-creation in the age of artificial intelligence, shifting from a logic of participation to one of "co-intelligence," where humans and intelligent systems jointly contribute to value creation.

Drawing on recent developments in digital innovation and service-dominant logic, this study explores how AI transforms the roles, boundaries, and dynamics of co-creation. It examines the evolving nature of agency, questioning whether AI should be considered a tool, a mediator, or an active co-creator. The paper also addresses critical issues related to authorship, control, and ethical responsibility, highlighting the risks of asymmetrical power distribution and algorithmic influence in collaborative processes.

Through a conceptual and exploratory approach, this research aims to enrich existing co-creation frameworks by integrating artificial intelligence as a central actor. It ultimately argues that understanding co-creation in contemporary contexts requires moving beyond human-centric paradigms toward hybrid, human–machine ecosystems of value generation. This shift has significant implications for organizations, public governance, and experience design, particularly in sectors increasingly shaped by digital transformation.

Keywords: Co-creation, Artificial Intelligence, Co-intelligence, Value Creation, Digital Transformation.

EXAMPLE

COMPARISON OF MINERAL CONTENT IN NOTHOGENUS ×*AMARINE* BULBS

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ABSTRACT

The intergeneric hybrid ×*Amarine* is an attractive but still relatively unknown ornamental plant. It is a hybrid between *Amaryllis belladonna* L. and *Nerine bowdenii*. The inflorescences of ×*Amarine tubergenii* are characterized by excellent postharvest longevity, making them a valuable product on the cut flower market. However, there is a lack of studies concerning the nutritional requirements and fertilization of ×*Amarine*, which limits the wider dissemination of this promising ornamental species. The aim of this study was to evaluate the mineral composition of bulbs of two taxa of ×*Amarine tubergenii*: 'Belladiva' and 'Zwanenburg'. Bulbs with an average fresh weight of 60.3 g ('Belladiva') and 40.5 g ('Zwanenburg') were analyzed after the dormancy period for selected macro- and micronutrients. Among macronutrients, the bulbs contained the highest amounts of nitrogen (1.80–3.00% DW), followed by potassium (0.89–0.94% DW), calcium (0.68–0.70% DW), phosphorus (0.24–0.25% DW), and magnesium (0.16–0.18% DW). Among micronutrients, iron was the most abundant (62.2–67.3 mg·kg^{-1} DW), followed by zinc (29.5–34.6 mg·kg^{-1} DW), copper (13.5–14.5 mg·kg^{-1} DW), boron (11.41–13.55 mg·kg^{-1} DW), and manganese (8.0–15.9 mg·kg^{-1} DW). Higher contents of nitrogen (+66%) and manganese (+80%) were found in the bulbs of ×*Amarine tubergenii* 'Zwanenburg'. In contrast, bulbs of ×*Amarine tubergenii* 'Belladiva' contained higher levels of boron (+18.8%), zinc (+17.3%), and iron (+8.03%). The obtained results may be useful for establishing threshold values necessary for diagnosing the mineral status of this new bulbous ornamental plant.

Keywords: chemical composition, geophytes, nutritional requirements, ornamental plants

EXAMPLE

COMMUNİTY PERCEPTİONS OF YOUTH-LED SUSTAİNABLE RURAL DEVELOPMENT İN PAMPLONA, CAMARİNES SUR, PHİLİPPİNES

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ABSTRACT

The Youth of Camarines Sur play a pivotal role in driving sustainable rural economic, social, and environmental development in the Philippines. Their participation and societal understanding, energy, and commitment to human rights and gender equality make them potential agents of change and transformation. This study aims to assess the project's performance and provide guidance for possible strategies and approaches to promote positive change in both students and educators. This mixed descriptive research assessed the performance of the teachers and the youth relevant to agriculture and rural development. A simple statistical technique and tool were used. The study is a Youth-led sustainable rural development project of Pamplona, Camarines Sur. The analyzed data revealed that the overall performance successfully attained its objectives and indicated an alignment of the activities with the intended purpose, in-place valuable interventions, and optimally used the resources. The study demonstrated sustainability through the integration of practical agricultural education into the curriculum, particularly through the utilization of the learning resources that show the local agricultural practices. The intervention strategies, including the provisions of school and community-based agricultural models, and the collaboration with stakeholders, effectively provided practical experience for students and young farmers, reinforcing the project's goals of capacity building and sustainable rural development. Mobility, restricted access to resources, and gaps in digital literacy are challenges encountered. Despite these challenges, the study delivered a significant and impactful life-changing opportunity for the beneficiaries. This suggests that the study has cultivated a feeling of satisfaction and ownership and established the foundation for more resilient and empowered rural communities. And, essential that logistical and digital challenges, as well as enhanced mentorship and community involvement, be strengthened as a strong foundation.

Keywords: *community project evaluation, sustainable rural agriculture program, learning assessment kits, young farmers*

ANTROPOSANTRİZMİN ÖTESİNDE MEKÂNSAL DİRENÇLİLİK: BİYOTASARIM VE MALZEME EYLEYİCİLİĞİ

REFRAMING SPATIAL RESILIENCE BEYOND ANTHROPOCENTRISM: MATERIAL AGENCY THROUGH BIODESIGN

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ÖZET

Bu çalışma, mimarlık söyleminde mekânsal dirençliliğin çoğunlukla yapısal dayanıklılık, stabilite ve bozulmaya karşı direnç gibi teknik parametreler çerçevesinde ele alındığını ve bu yaklaşımın malzemeyi edilgen, kontrol edilebilir ve insan iradesine tabi bir nesne olarak konumlandıran antroposantrik bir tasarım paradigmasına dayandığını ileri sürmektedir. Dirençlilik kavramının bu dar yorumu, mekânı statik bir performans alanı olarak tanımlamakta ve malzemenin ekolojik bağlamla kurduğu ilişkileri ikincil plana itmektedir. Çalışma, çağdaş mimari üretimin epistemolojik temellerini sorgulayarak, dirençliliğin yalnızca dışsal tehditlere karşı gösterilen bir mukavemet değil, ekolojik sistemler içinde gelişen ilişkisel, süreçsel ve uyarlanabilir bir kapasite olarak yeniden düşünülmesi gerektiğini savunmaktadır.

Biyotasarım araştırmaları, biyolojik tasarım ilkeleri ve ekolojik dirençlilik literatüründen beslenen bu kavramsal inceleme, malzeme eyleyiciliğini (material agency) mekânsal üretimin dağıtık ve etkin bir unsuru olarak konumlandırmaktadır. Yumurta kabuğu atıklarından elde edilen kalsiyum karbonat kompozitler, miselyum temelli büyüme sistemleri ve süt proteinlerinden türetilen kazein bazlı biyopolimerler gibi örnekler, bu ontolojik dönüşümün maddi tezahürleri olarak ele alınmaktadır. Bu biyoloji temelli malzemeler; değişkenlik, çevresel duyarlılık, döngüsellik ve yaşam döngüsü bütünleşmesi gibi özellikleriyle, endüstriyel üretim sistemlerinin homojenlik, kalıcılık ve merkezi kontrol varsayımlarını sorgulamakta ve mekânın sabit değil dönüşebilir bir organizasyon olarak ele alınmasına imkân tanımaktadır.

Çalışma, kuramsal olarak tasarım epistemolojisine katkı sunarak mimari üretimi insan ve insan-dışı aktörler arasında gerçekleşen ilişkisel bir müzakere süreci olarak yeniden konumlandırmaktadır. Kavramsal olarak ise mekânsal dirençliliği yapısal dayanıklılıktan ziyade uyarlanabilir dönüşüm ve ekolojik katılım kapasitesi olarak tanımlamaktadır. Bu çerçeve, mekânsal araştırmalar için antroposantrizm ötesi ve ekolojik gömülülüğü esas alan yeni bir düşünsel yönelim önermektedir.

Anahtar Kelimeler: Mekânsal dirençlilik, Biyotasarım, Malzeme eyleyiciliği, antroposantrizm, İlişkisel ontoloji, Tasarım epistemolojisi

TASARIM

ABSTRACT

This paper critically examines how the conceptualization of spatial resilience within architectural discourse remains largely embedded in an anthropocentric design paradigm that positions materials as passive, controllable objects subjected to human intention. Within this prevailing framework, resilience is predominantly interpreted as structural endurance, stability, or resistance to external disturbance. Such a perspective reduces spatial systems to technical assemblages and overlooks the relational and ecological dimensions through which material processes unfold. By interrogating the epistemological foundations of conventional architectural production, the study argues for a fundamental shift toward relational ontologies of matter and agency, proposing that resilience should be understood not as static resistance but as adaptive participation within dynamic ecological systems.

Drawing on interdisciplinary scholarship in biodesign, biological design principles, and ecological resilience theory, the paper develops a conceptual framework that reconfigures material agency as a distributed and active capacity shaping spatial formation, transformation, and performance over time. Illustrative material instances—including calcium carbonate composites derived from eggshell waste, mycelium-grown structural systems, and casein-based biopolymers synthesized from milk proteins—are discussed as epistemological evidence of this ontological reorientation. These bio-based materials foreground variability, environmental responsiveness, cyclical regeneration, and lifecycle integration, thereby challenging industrial assumptions of permanence, homogeneity, and centralized control.

By positioning bio-based matter as more than sustainable substitutes, the study demonstrates how relational material ecologies can cultivate a post-anthropocentric understanding of resilience grounded in adaptability, ecological co-constitution, and temporal transformation. The paper contributes theoretically to design epistemology by reframing architectural practice as an ongoing negotiation among human and non-human actors. Conceptually, it redefines spatial resilience as adaptive transformation rather than structural endurance. This relational perspective opens new methodological and theoretical pathways for architectural research and practice centered on ecological embeddedness and material co-agency.

Keywords: Spatial resilience, Biodesign, Material agency, Anthropocentrism, Relational ontology

EXAMPLE

MODÜLERLİK VE BAĞLANTISALLIK ÜZERİNDEN MEKÂNSAL DİRENÇLİLİĞİN DEĞERLENDİRİLMESİ: TASARIM TEMELLİ BİR YAKLAŞIM

SPATIAL RESILIENCE ASSESSMENT THROUGH MODULARITY AND CONNECTIVITY: A DESIGN-BASED APPROACH

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ÖZET

Dirençlilik, mimari ve mekânsal sistemlerin belirsizlik koşulları altında uyarlanabilir biçimde yeniden örgütlenmesini açıklayan temel kavramlardan biri haline gelmiştir. Ancak kavramın yaygın kullanımına rağmen, mekânsal dirençliliğin ölçülebilir ve tasarım sürecine entegre edilebilir biçimde ele alınması sınırlı kalmıştır. Bu çalışma, mekânsal dirençliliği iki temel örgütlenme özelliği üzerinden değerlendiren analitik bir çerçeve önermektedir: modülerlik ve bağlantısallık.

Çalışmada 134 birbirine kenetlenen modülden oluşan bir mekânsal sistem oluşturulmuş ve grafik-temelli ölçütler kullanılarak analiz edilmiştir. Modülerlik, Newman Modülerlik İndeksi ($Q = 0.637$) ile değerlendirilmiş ve sistemin kümelenmiş yapıda olduğu, dolayısıyla içsel yeniden örgütlenme kapasitesi taşıdığı ortaya konmuştur. Bağlantısallık ise Beta ($\beta = 2.739$), Gamma ($\gamma = 0.927$) ve Alpha ($\alpha = 0.890$) indeksleri kullanılarak analiz edilmiş; sistemin yüksek ilişkisel yoğunluğa, alternatif döngülere ve güçlü topolojik bütünlüğe sahip olduğu gösterilmiştir.

Elde edilen bulgular, modülerlik ve bağlantısallığın dirençliliği yalnızca kavramsal bir ideal olarak değil, ölçülebilir ve tasarıma entegre edilebilir bir özellik olarak değerlendirmeyi mümkün kıldığını göstermektedir. Bu bağlamda mekânsal dirençlilik, adaptif, esnek ve stratejik olarak örgütlenmiş çevreler üretebilen içsel bir organizasyon mantığı olarak yeniden konumlandırılmaktadır. Çalışma ayrıca bu çerçevenin, uyarlanabilirlik, çeşitlilik ve kullanıcı etkileşimi gibi diğer dirençlilik öznitelikleriyle genişletilebileceğini ve dijital simülasyon ile fiziksel prototipleme yoluyla güçlendirilebileceğini önermektedir. Sonuç olarak bu araştırma, modüler sistemlerde dirençliliğin yapısal temellerini incelemek için tekrarlanabilir bir metodoloji sunmakta ve mekânsal tasarım çalışmalarına aktarılabilir bir analitik model önermektedir.

Anahtar Kelimeler: Mekânsal dirençlilik, Modüler sistemler, Tasarım bazlı araştırma

EXAMPLE

ABSTRACT

Resilience has increasingly become a central framework through which architectural and spatial systems are understood to adapt under conditions of uncertainty. However, despite its widespread use in urban and infrastructural studies, measurable and design-integrated approaches to spatial resilience remain relatively underdeveloped. This study proposes an analytical framework to evaluate spatial resilience through two key organizational attributes: modularity and connectivity, within a modular system model.

A spatial configuration composed of 134 interlocking modules was constructed and analyzed using graph-based metrics. Modularity was assessed through Newman's Modularity Index ($Q = 0.637$), indicating clustered organization and inherent reorganizing capacity within the system. Connectivity was examined using Beta ($\beta = 2.739$), Gamma ($\gamma = 0.927$), and Alpha ($\alpha = 0.890$) indices, demonstrating high relational density, multiple alternative cycles, and strong topological coherence across the network.

The findings reveal that modularity and connectivity together enable resilience to be interpreted not only as a conceptual aspiration but as a quantifiable and design-embedded property. In this perspective, spatial resilience is repositioned as an internal organizational logic capable of generating adaptive, flexible, and strategically structured environments. The study further suggests that this analytical framework may be expanded by integrating additional resilience attributes such as adaptability, diversity, and user interaction, and validated through digital simulations and physical prototyping. Overall, the research provides a replicable methodology for investigating the structural underpinnings of resilience within modular systems and offers a transferable analytical model for future spatial design research.

Keywords: Spatial resilience, Modular systems, Design-led researc

EXAMPLE

EXAMPLE

ALT EKSTREMİTE AMPUTELERİNDE ÇİFT GÖREV (DUAL-TASK) PERFORMANSININ YÜRÜME VE DENGE ÜZERİNE ETKİLERİ

EFFECTS OF DUAL-TASK PERFORMANCE ON GAIT AND BALANCE IN INDIVIDUALS WITH LOWER EXTREMITY AMPUTATION

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ÖZET

Alt ekstremite amputasyonu geçiren bireylerde rehabilitasyonun temel hedefleri arasında yürüme ve dengenin iyileştirilmesi yer almaktadır. Günlük yaşam aktivitelerinin önemli bir bölümü ise bireyin aynı anda hem motor hem de bilişsel süreçleri yönetmesini gerektirir. Bu tür durumlar literatürde çift görev (dual-task) olarak ifade edilmekte ve güvenli hareket açısından önemli bir rol oynamaktadır. Ampute bireyler yürüyüş sırasında artan bilişsel gereksinimler nedeniyle çift görev koşullarında performans kaybı yaşayabilmektedir. Bu derleme, motor ve bilişsel görevlerin birlikte yürütülmesinin alt ekstremite amputeleri üzerindeki yürüme ve denge performansı üzerindeki etkilerini incelemeyi amaçlamaktadır. Bu kapsamda PubMed, Scopus ve Google Scholar veri tabanlarında alt ekstremite amputasyonu, çift görev, yürüme, denge ve rehabilitasyon anahtar kelimeleri kullanılarak yayımlanan güncel çalışmalar incelenmiştir. Literatürde, özellikle çift görev koşullarında yürüme performansının olumsuz etkilendiği görülmektedir. Bu durum; yürüme hızında ve kadansda azalma ile adım süresinde uzama ve stabilitede bozulma şeklinde ortaya çıkmaktadır. Söz konusu değişiklikler, artan bilişsel yükün motor kontrol ve performans üzerinde belirleyici bir rol oynadığını göstermektedir. Sonuç olarak, çift görev sırasında ortaya çıkan performans değişiklikleri alt ekstremite amputelerinde mobilite ve güvenliği etkileyen önemli bir faktördür. Bu nedenle, fizyoterapi programlarında çift görev yaklaşımlarına yer verilmesinin fonksiyonel bağımsızlığı artırabileceği ve düşme riskini azaltabileceği düşünülmektedir.

Anahtar Kelimeler: Alt ekstremite amputasyonu, Çift görev, Yürüme, Denge, Rehabilitasyon

EXAMPLE

ABSTRACT

Restoring gait and balance is one of the primary goals in the rehabilitation of individuals with lower extremity amputation. In daily life, many activities require the simultaneous management of motor and cognitive processes, commonly referred to as dual-task conditions, which are essential for maintaining safe mobility. Individuals with amputation often experience additional difficulty in such situations, as walking itself requires increased attention and control; therefore, performance may decline when an additional cognitive task is introduced. This review examines how performing motor and cognitive tasks together affects gait and balance in individuals with lower extremity amputation. For this purpose, recent studies published in PubMed, Scopus, and Google Scholar were analyzed using keywords such as lower extremity amputation, dual-task, gait, balance, and rehabilitation. This condition is characterized by reductions in gait speed and cadence, accompanied by prolonged step time and impaired stability. These alterations suggest that increased cognitive load exerts a significant influence on motor control and overall performance. Accordingly, the effects observed during dual-task conditions represent a critical factor affecting mobility and safety in individuals with lower extremity amputation. Therefore, the integration of dual-task paradigms into physiotherapy interventions may contribute to improved functional independence and a reduction in fall risk.

Keywords: Lower extremity amputation, Dual-task, Gait, Balance, Rehabilitation

EXAMPLE

BREAST CANCER AS A BİOELECTRİCAL DİSORDER: EXPLORİNG THE ROLE OF MEMBRANE POTENTİAL DYNAMİCS AND ION FLUX SİGNALLİNG

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ABSTRACT

Breast cancer is interpreted with respect to genetic and molecular changes. Still, recent studies indicate that it is a bioelectrical disease, with membrane potential disturbance and ion flux playing a key role in cancer development and progression. This paper will examine the importance of the modified bioelectric signal, especially variations in transmembrane potential and ion channels, in the development of breast cancer. An extensive review of the literature available was used to assess the connection between depolarised membrane potential, dysregulated ion transport (calcium, potassium, and sodium ions), and the behaviour of cancer cells. Results indicate that cancerous cells have a more depolarised state than normal cells, which leads to an increase in proliferation, migration and metastatic potential. Also, abnormal expression of ion channels affects intracellular signalling pathways, thereby enhancing tumour growth and resistance to apoptosis. The discussion highlights the role that bioelectrical markers can play as diagnostic and prognostic methods, and the new therapeutic targets in the management of breast cancer. The concept of breast cancer as a bioelectrical disease is a fresh insight that can be used to supplement the established molecular methodologies, and thus, to bring new ideas to the multi-billion-dollar business of breast cancer screening and treatment.

EXAMPLE

SİVAS HARALAR BÖLGESİ RESTORASYON UYGULAMASI VE KENT ÖLÇEĞİNDE DEĞERLENDİRİLMESİ

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ÖZET

Bu çalışma, Sivas'ta II. Abdülhamid döneminde savaş atı yetiştirme amacıyla inşa edilen Hamidiye Haraları'nın restorasyon sürecini ve kent ölçeğindeki etkilerini incelemektedir. Tarihsel önemine karşın Cumhuriyet sonrasında işlevini yitiren ve uzun süre atıl kalan alan, 2018 yılında başlatılan restorasyon ve peyzaj çalışmalarıyla yeniden ele alınmış; korunarak yeni işlevlerle toplumsal yaşama kazandırılmıştır. Araştırmada restorasyon, yeniden işlevlendirme, kentsel bellek ve kentsel tasarım kavramları Venedik Tüzüğü ilkeleri çerçevesinde değerlendirilmiştir.

Çalışmanın amacı, Sivas'taki bu geniş çaplı koruma uygulamasını inceleyerek literatüre katkı sunmak ve yeni eklemelerle birlikte alanın kentli tarafından yerel ölçekte nasıl algılandığını ortaya koymaktır. Bu doğrultuda nitel ve nicel araştırma yöntemleri birlikte kullanılmış; akademik yayınlar, kurul raporları ve alan verileri üzerinden değerlendirme yapılmıştır.

Bulgular, Haralar Bölgesi'nin yalnızca fiziksel bir restorasyon alanı olmadığını, aynı zamanda kentsel belleği yeniden üreten önemli bir kamusal odak haline geldiğini göstermektedir. Savaş Atları Müzesi, Camekan Kafe, Hara Restoran, Abdülhamid Han Anı Evi ve Şale Kitap Kafe gibi işlevler, alanın kültürel ve sosyal çekiciliğini artırmıştır. Bununla birlikte kent merkeziyle olan mesafe, toplu taşıma eksikliği ve tanıtım yetersizliği, kullanım sürekliliğini sınırlayan temel sorunlar olarak öne çıkmaktadır.

Sonuç olarak çalışma, koruma ve yeniden işlevlendirme dengesinin büyük ölçüde başarıyla kurulduğunu; ancak alanın kent yaşamına daha güçlü biçimde entegre olabilmesi için ulaşım, tanıtım ve kullanıcı odaklı stratejilerin geliştirilmesi gerektiğini ortaya koymaktadır. Ayrıca alanın millet bahçesi niteliği, binicilik, yeme-içme ve rekreasyon işlevleriyle desteklenmesi, karayolu güzergâhında yer alması sayesinde ziyaretçilere alternatif bir turistik durak sunmaktadır. Bu yönüyle proje, tarihî çevrenin korunmasını ekonomik canlanma, kültürel görünürlük ve kamusal kullanım sürekliliği ile ilişkilendiren çok boyutlu bir dönüşüm örneği oluşturmaktadır.

Anahtar sözcükler: Restorasyon, Yeniden İşlevlendirme, Kentsel Bellek, Kentsel Tasarım, Sivas Haralar Bölgesi

RESTORATION APPLICATION OF THE SIVAS HARAS REGION AND ITS EVALUTION AT THE URBAN SCALE

ABSTRACT

This study examines the restoration process of the Hamidiye Haras in Sivas, originally constructed during the reign of Sultan Abdülhamid II for breeding war horses, and evaluates its effects at the urban scale. Despite its historical significance, the site lost its original function after the establishment of the Republic and remained abandoned for a long period. In 2018, the area was reconsidered through restoration and landscape interventions, and it was reintegrated into public life through conservation and adaptive reuse.

Within the scope of the project, key concepts such as restoration, adaptive reuse, urban memory, and urban design were evaluated in accordance with the principles of the Venice Charter. The aim of the study is to contribute to the literature by analyzing this large-scale conservation practice in Sivas and to reveal how the area, together with its new additions, is perceived by urban users at the local scale. For this purpose, qualitative and quantitative research methods were used together, and the evaluation was based on academic publications, conservation board reports, and field data.

The findings indicate that the Haras Region is not merely a physically restored site, but also an important public focal point that reconstructs urban memory. Functions such as the War Horses Museum, Camekan Café, Hara Restaurant, Abdülhamid Han Memorial House, and Şale Book Café have increased the cultural and social attractiveness of the area. However, the distance from the city center, inadequate public transportation, and insufficient promotion stand out as the main factors limiting continuity of use.

Consequently, the study concludes that the balance between conservation and adaptive reuse has largely been achieved successfully; however, transportation, promotion, and user-oriented strategies should be developed to integrate the site more strongly into urban life.

Keywords: Sivas School Of Industry, Sivas Archaeology Museum, Adaptive Reuse, Cultural Heritage, Museology, Social Memory

EXAMPLE

DESİGN AND CHARACTERİZATİON OF NEW II-CONJUGATED QUİNOXALİNE DERİVATİVES FOR SOLAR CELLS: A TD-DFT STUDY

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ABSTRACT

Using DFT/TD-DFT calculations, this theoretical study investigates four quinoxaline-based derivatives (M1–M4) as potential electron donors for organic solar cells (OSCs). M3 stands out as the premier candidate due to its narrow band gap, expansive absorption spectrum, and high chemical softness—attributes that facilitate enhanced light harvesting and charge transport. Although M1 and M2 possess deeper HOMO levels, which could improve open-circuit voltage, their wider band gaps restrict overall absorption efficiency. These findings highlight how strategic molecular engineering can optimize quinoxaline derivatives for advanced photovoltaic performance.

Keywords: Quinoxaline derivatives, Organic solar, TD-DFT, photovoltaic applications, Energy bandgap

EXAMPLE

EMPOWERİNG WOMEN THROUGH CLİMATE-SMART AGRİCULTURE: EVİDENCE FROM RURAL COMMUNİTİES

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ABSTRACT

In semi-arid regions like Karauli, agriculture is characterized by erratic rainfall, limited irrigation, and high vulnerability, particularly for small and marginal farmers. Women farmers, despite playing a critical role in agriculture, often face constraints related to access to resources, decision-making, and market linkages. This paper examines how climate-smart agriculture (CSA) interventions can contribute to women's empowerment and improved rural livelihoods through a field-based case study.

The study focuses on Poonam Meena, a small farmer from Harnagar panchayat, who transitioned from traditional mono-cropping of wheat to diversified vegetable cultivation on a small plot of
0.25 bigha land. With support from SRIJAN, she adopted climate-smart practices including mixed cropping, use of bio-inputs, and natural farming techniques. The intervention involved the provision of a vegetable kit and capacity-building support through community institutions.

The results demonstrate a significant improvement in economic outcomes. Net income increased from ₹5,000 under wheat cultivation to ₹9,900 through diversified vegetable farming within one cropping cycle, reflecting a nearly 98% rise in income. Additionally, dependence on external markets reduced as the farmer began direct selling, enhancing profit margins. Beyond income, the intervention contributed to improved household nutrition, reduced climate risks, and better soil health.

Importantly, the transition led to enhanced agency and decision-making power for the woman farmer within the household and community. The findings highlight that climate-smart agriculture, when integrated with a gender-sensitive and community-based approach, can serve as an effective tool for women's empowerment and sustainable rural development.

Keywords: Climate-Smart Agriculture, Women Empowerment, Rural Livelihoods, Crop Diversification, Sustainable Development

EXAMPLE

RADIO-FREQUENCY PLASMA POLYMERIZATION OF N,N-DIMETHYLANILINE: SYNTHESIS AND COMPREHENSIVE CHARACTERIZATION OF THIN FILMS

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ABSTRACT

The present study reports the synthesis and characterization of polymer thin films derived from the N,N-dimethylaniline monomer using radio-frequency (RF) plasma polymerization. The thickness of the deposited polymer films, measured by ellipsometry, is approximately 200 nm. The films were characterized using UV–Visible spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, and X-ray diffraction (XRD). The DC conductivity was observed to increase with temperature, indicating semiconducting behavior. XRD analysis confirms the amorphous nature of the synthesized polymer films. The full width at half maximum (FWHM) obtained from the UV–Visible spectrum is 18.4 nm. A notable finding of this study is the negative absorbance observed in the UV–Visible absorption spectrum, attributed to the variation of optical density with incident photon wavelength. This unique feature suggests potential applications in novel UV-transmitting devices. The successful polymerization of N,N-dimethylaniline was further confirmed by FTIR analysis.

Keywords: RF plasma polymerization; N,N-dimethylaniline; polymer thin films; UV–Visible spectroscopy; DC conductivity; negative absorbance.

EXAMPLE

TİTANİUM-MEDİATED SYNTHESİS AND PD-CATALYZED DERİVATİZATİON OF THİOPHENE CARBOXYLATES: ANTİBACTERİAL EVALUATİON AGAİNST NDM-B LACTAMASE-PRODUCİNG KLEBSİELLA PNEUMONİAE (ST147)

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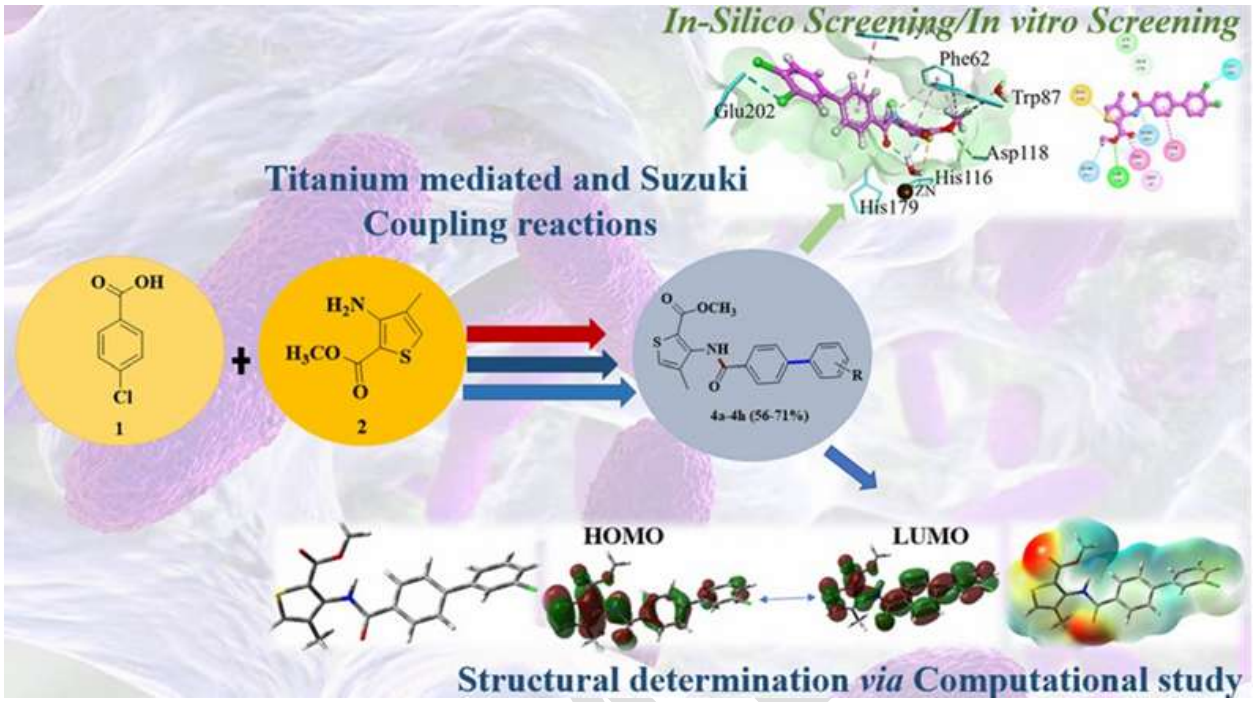
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ABSTRACT

NDM-1-KP ST 147 remains a serious challenge in clinical practice, primarily due to its increasing resistance to carbapenems and its hypervirulent characteristics. A range of virulence factors is involved in this hypervirulence, and the mechanisms underlying carbapenem resistance are complex and multifaceted. The NDM KP (ST147) has emerged as a recent addition to the family of successful clones within the species. In this study, we synthesized methyl 3-(4-chlorobenzamido) 4-methylthiophene-2-carboxylate (**3**) by reacting amino thiophene (**1**) with 4-bromobenzoic acid (**2**) in the presence of TiCl4 (catalyst) and pyridine. The Suzuki coupling of compound (**3**) led to the synthesis of a library of derivatives (**4a 4f**), which were obtained with yields varying from 56% to 71%. Subsequently, the synthesized molecules (**4a-4h**) were assessed for their antibacterial activity against clinically isolated NDM-β-lactamase (ST147). Further, In silico studies were carried out by using protein with the PDB ID: 5N5I, derived from NDM-KP (ST147). The chloro-substituted molecule **4e**, which shows potential as a drug candidate (MIC = 3.125 µg/mL and MBC = 6.25 µg/mL), displayed the highest level of effectiveness against resistant bacterial strains. Moreover, DFT calculations were employed to determine the frontier molecular orbitals, molecular electrostatic potential (MEP) maps, HOMO-LUMO energy values, hyperpolarizability, and reactivity descriptors for each compound. In this series, compound 4c, where biphenyl is substituted with OCH_3, exhibits the smallest energy gap of 4.24 eV and 4.51 eV, along with the highest hyperpolarizability values of 5495.62 Hatree. This compound, being the least stable, results in the most significant nonlinear optical (NLO) response. In the next phase of the *in vivo* experimental trial, the lead molecule could present an alternative therapeutic option.


In-Silico Screening/In vitro Screening
Phe62
Trp87
Glu202
Asp118
His116
ZN
His179
Titanium mediated and Suzuki
Coupling reactions
OH
Cl
1
H_2N
H_3CO
S
O
2
OCH_3
NH
R
4a-4h (56-71%)
HOMO
LUMO
Structural determination *via* Computational study

EXAMP

KANNABİDİOL (CBD)'ÜN KORNEAL YARA İYİLEŞMESİ ÜZERİNE ETKİLERİ

THE EFFECTS OF CANNABIDIOL (CBD) IN CORNEAL WOUND HEALING

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ÖZET

Kornea ülserleri, veteriner oftalmolojide sık karşılaşılan ve uygun tedavi edilmediğinde ciddi görme kaybına yol açabilen oküler yüzey hastalıklarıdır. Bu süreçte inflamasyon, ağrı, epitel bütünlüğünün bozulması ve sekonder enfeksiyonlar iyileşmeyi geciktiren temel faktörlerdir. Mevcut tedavilere rağmen iyileşme süreci uzun sürebilir ve çoğu zaman kalıcı görme kaybı gelişebilir. Son yıllarda kanabinoidler, özellikle de kannabidiol (CBD), korneal iyileşmede potansiyel bir ajan olarak dikkat çekmektedir. CBD; anti-inflamatuvar, analjezik, antioksidan ve doku onarımını destekleyici özellikler gösterebilir. Etkilerini doğrudan güçlü bir agonist olarak değil, daha çok CB_1 ve CB_2 reseptörlerini dolaylı modüle ederek ortaya koyar. CB_1 reseptörleri özellikle kornea epitelinde bulunur ve ağrı ile inflamasyonun düzenlenmesinde rol oynar. CB_2 ise daha çok immün yanıt ve inflamasyon kontrolü ile ilişkilidir. Bunun dışında CBD; TRPV1, GPR18 ve 5-HT1A gibi farklı reseptörler üzerinden de etki gösterir. TRPV1 üzerinden ağrı sinyallerini azaltır, 5-HT1A aracılığıyla inflamasyonu baskılar ve GPR18 üzerinden hücresel göç ve proliferasyonu etkileyerek yara iyileşmesine katkı sağlayabilir. Ayrıca anjiyogenez dengesini düzenleyerek korneal neovaskülarizasyonu sınırlayabileceği düşünülmektedir. Deneysel çalışmalar, CBD'nin korneal inflamasyonu azaltabileceğini, ağrıyı hafifletebileceğini ve iyileşme sürecini destekleyebileceğini göstermektedir. Ancak mevcut veriler büyük ölçüde deneysel düzeydedir ve klinik kullanım için yeterli kanıt henüz oluşmamıştır. Sonuç olarak CBD, korneal iyileşme açısından umut verici bir molekül olsa da veteriner hekimlikte rutin kullanımını destekleyecek güçlü klinik çalışmalara ihtiyaç vardır.

Anahtar Kelimeler: Kornea ülseri, Kannabidiol, İnflamasyon, Yara iyileşmesi

ABSTRACT

Corneal ulcers are common ocular surface diseases in veterinary ophthalmology that can lead to severe vision loss if not treated appropriately. In this process, inflammation, pain, disruption of epithelial integrity, and secondary infections are the primary factors delaying healing. Despite current treatments, the healing process can be prolonged, and permanent vision loss often develops. In recent years, cannabinoids, particularly cannabidiol (CBD), have garnered attention as a potential agent for corneal healing. CBD may exhibit anti-inflammatory, analgesic, antioxidant, and tissue-repairing properties. It exerts its effects not as a direct, potent agonist, but rather by indirectly modulating CB_1 and CB_2 receptors. CB_1 receptors are primarily found in the corneal epithelium and play a role in regulating pain and inflammation. CB_2, on the other hand, is primarily associated with immune response and inflammation control. Additionally, CBD exerts effects through various receptors such as TRPV1, GPR18, and 5-HT1A. It reduces pain signals via TRPV1, suppresses inflammation through 5-HT1A, and may contribute to wound healing by influencing cellular migration and proliferation via GPR18. It is also thought to limit corneal neovascularization by regulating the balance of angiogenesis. Experimental studies suggest that CBD may reduce corneal inflammation, alleviate pain, and support the healing process. However, the current data are largely experimental, and sufficient evidence for clinical use has not yet been established. Consequently, while CBD is a promising molecule for corneal healing, robust clinical studies are needed to support its routine use in veterinary medicine.

Keywords: Corneal ulcer, Cannabidiol, Inflammation, Wound healing

YAYIN

MAGNETICALLY RESPONSIVE POLIMER MATRIX NANOCOMPOSITES

MANYETİK TEPKİLİ POLİMER MATRİS NANOKOMPOZİTLER

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EXAMPLE

ÖZET

Polimer esaslı kompozit malzemeler, düşük yoğunlukları, kolay işlenebilirlikleri ve ayarlanabilir çok fonksiyonlu özellikleri nedeniyle son yıllarda önemli ilgi görmektedir. Bu çalışmada, nanoparçacıkların polimer karışımına ilavesiyle manyetik fonksiyonel polimer nanokompozitler başarıyla üretilmiştir. Geliştirilen malzemelerin termal, yapısal, morfolojik ve manyetik özelliklerini sistematik olarak değerlendirmek amacıyla TGA, DSC, FTIR, XRD, SEM ve PPMS teknikleri kullanılarak kapsamlı karakterizasyon gerçekleştirilmiştir.

Termogravimetrik analiz, nanoparçacık ilavesi sonrasında bozunma başlangıç sıcaklıklarının artması ve artık kütle değerlerinin yükselmesi ile termal kararlılığın belirgin biçimde iyileştiğini göstermiştir. Diferansiyel taramalı kalorimetri sonuçları, özellikle yüksek dolgu oranında (%40 a/h) erime sıcaklığı ve kristalleşme davranışında dolguya bağlı değişimler ortaya koymuş; bu durum polimer zincir hareketliliği ve kristalin organizasyon üzerinde güçlü bir etkiye işaret etmiştir. FTIR spektrumları, nanoparçacıklar ile polimer matrisi arasında yeni kovalent bağ oluşmadığını doğrularken, büyük olasılıkla hidrojen bağları olmak üzere moleküller arası etkileşimlerin varlığını göstermiştir. XRD analizleri, yarı kristalin polimer matrisinin baskın faz olarak korunduğunu, demir oksitlere ait karakteristik kristal piklerinin ise nanoskopik dağılım ve homojen dispersiyon nedeniyle belirgin şekilde bastırıldığını ortaya koymuştur. SEM gözlemleri, düşük dolgu oranlarında nanoparçacıkların nispeten homojen dağıldığını göstermiştir.

Sonuç olarak, polimer matrisine nanoparçacık ilavesinin PCL–PVA nanokompozitlerin çok fonksiyonlu performansını etkili biçimde uyarladığı ve bu malzemelerin algılama, aktüasyon, biyomedikal mühendislik ve manyetik ayırma teknolojileri gibi ileri uygulamalar için güçlü bir potansiyel taşıdığı belirlenmiştir.

Anahtar Kelimeler: manyetik polimer nanokompozitler, PCL–PVA karışımı, demir oksit nanoparçacıkları, termal kararlılık, manyetik özellikleri

İ.Ü.(BAP) FBA-2025 3826 projesi ile desteklenmiştir.

MAGNETICALLY RESPONSIVE POLIMER MATRIX NANOCOMPOSITES

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EXAMPLE

ABSTRACT

Polymer-based composite materials have attracted significant attention in recent years due to their low density, ease of processing, and adjustable multifunctional properties. In this study, magnetic functional polymer nanocomposites were successfully produced by adding nanoparticles to a polymer mixture. Comprehensive characterization was performed using TGA, DSC, FTIR, XRD, SEM, and PPMS techniques to systematically evaluate the thermal, structural, morphological, and magnetic properties of the developed materials.

Thermogravimetric analysis showed that thermal stability improved significantly after the addition of nanoparticles, as evidenced by an increase in the onset decomposition temperatures and an increase in the residual mass values. Differential scanning calorimetry results revealed filler-dependent changes in melting temperature and crystallization behavior, particularly at high filler content (40 wt%), indicating a strong effect on polymer chain mobility and crystalline organization. FTIR spectra confirmed that no new covalent bonds formed between the nanoparticles and the polymer matrix, while indicating the presence of intermolecular interactions, most likely hydrogen bonds. XRD analyses revealed that the semi-crystalline polymer matrix was preserved as the dominant phase, while the characteristic crystal peaks of iron oxides were significantly suppressed due to nanoscopic distribution and homogeneous dispersion. SEM observations showed that nanoparticles were relatively homogeneously distributed at low filler ratios.

In conclusion, the addition of nanoparticles to the polymer matrix effectively adapts the multifunctional performance of PCL–PVA nanocomposites, and these materials have been determined to hold strong potential for advanced applications such as sensing, actuation, biomedical engineering, and magnetic separation technologies.

Keywords: magnetic polymer nanocomposites, PCL–PVA blend, iron oxide nanoparticles, thermal stability, magnetic properties

Supported by Inonu University (BAP) FBA-2025 3826 project.

GAMMA-RAY SHIELDING PERFORMANCE OF POLYESTER COMPOSITES REINFORCED WITH MICRO AND NANO SIZED BARIUM TITANATE PARTICLES

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EXAMPLE

ABSTRACT

Ionizing radiation is widely used in daily life in fields such as industry and medicine, and in cases of long-term exposure, it adversely affects human health. Therefore, the development of radiation shielding materials is of great importance for us. Conventional lead-based shielding materials have formed the basis of the search for alternative materials due to their toxicity and high density. In this study, it is aimed to develop polymer-based composite shielding materials that are lighter, non-toxic, and environmentally friendly as an alternative to lead. For this purpose, composite structures were obtained by incorporating micro- and nano-sized barium titanate ($BaTiO_3$), which has a high atomic number, into a polyester matrix at different ratios. The gamma-ray shielding performance of the obtained composites was determined experimentally. The experimental data were obtained using a NaI(Tl) detector under narrow beam geometry for gamma-ray energies emitted from Ba-133, Cs-137, and Co-60 radioactive sources. The radiation shielding performance of the composites was examined in terms of mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) parameters. At low energies, it was determined that the addition of $BaTiO_3$ significantly increased the radiation attenuation properties of the polyester material. Among all composites, the PE/20% n$BaTiO_3$ composite with the highest nano-sized $BaTiO_3$ concentration showed the best gamma-ray shielding performance at low energies. The mass attenuation coefficient of this composite at 81 keV was measured as 0.83 cm^2/g.

Keywords: Radiation shielding, Polymer composites, Barium titanate, Nanocomposite, Mass attenuation coefficient

MİKRO VE NANO BOYUTLU BARYUM TİTANAT KATKILI POLİESTER KOMPOZİTLERİN GAMA IŞINI ZIRHLAMA PERFORMANSI

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EXAMPLE

ÖZET

İyonize radyasyon, günlük hayatımızda yaygın şekilde endüstri, tıp gibi alanlarda kullanılmakta olup, uzun süre maruz kalındığı durumlarda ise insan sağlığını olumsuz etkilemektedir. Bu sebeple, radyasyon zırhlayıcı malzemelerin geliştirilmesi bizler için büyük önem taşımaktadır. Geleneksel olarak kullanılan kurşun temelli zırhlayıcılar toksik ve ağır olmaları nedeniyle alternatif malzeme arayışlarının temelini atmıştır. Bu çalışmada, kurşuna alternatif olarak daha hafif, toksik olmayan ve çevre dostu polimer yapılı kompozit zırhlayıcıların geliştirilmeesi amaçlanmıştır. Bu amaçla poliester matrise yüksek atom numarasına sahip nano ve mikro boyutta baryum titanat ($BaTiO_3$) farklı oranlarda katkılandırılarak kompozit yapılar elde edilmiştir. Elde edilen kompozitlerin gama ışını zırhlama performansı deneysel olarak belirlenmiştir. Deneysel veriler, dar ışın geometrisinde NaI(Tl) dedektörü kullanılarak, Ba-133, Cs-137 ve Co-60 radyoaktif kaynaklarından yayılan gama ışını enerjileri için elde edilmiştir. Kompozitlerin radyasyon zırhlama performansı kütle azaltma katsayısı (MAC), yarı değer kalınlığı (HVL), onda bir değer kalınlığı (TVL) ve ortalama serbest yol (MFP) parametreleri ile incelenmiştir. Düşük enerjilerde, $BaTiO_3$ ilavesinin poliester malzemenin radyasyon zayıflatma özelliklerini önemli ölçüde artırdığı belirlenmiştir. Tüm kompozitler arasında, en yüksek nano boyutlu $BaTiO_3$ konsantrasyonuna sahip olan PE/%20 n$BaTiO_3$ kompoziti, düşük enerjilerde en iyi gama ışını zırhlama performansını göstermiştir. Bu kompozitin 81 keV deki kütle azaltma katsayısı 0,83 cm^2/g olarak ölçülmüştür.

Anahtar Kelimeler: Radyasyon zırhlama, Polimer kompozitler, Baryum titanat, Nano kompozit, kütle azaltma katsayısı

ADAPTIVE REUSE OF THE SIVAS SCHOOL OF INDUSTRY MUSEUM AND THE ARCHEOLOGY MUSEUM

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Abstract

This paper examines the adaptive reuse of the Sivas School of Industry and the former blacksmith workshop located nearby as museum spaces within their historical, architectural, and social dimensions. Built in 1902 during the reign of Sultan Abdülhamid II, the Sivas School of Industry is regarded as one of the spatial reflections of the modernization and industrialization policies of the Ottoman Empire. It stands out as a significant building, particularly because it was established to provide vocational skills to orphaned children, thereby reflecting the educational and social policy approach of its period.

Over time, the building served different functions and continued its existence during the Republican era. Following comprehensive restoration works completed in 2019, it was reopened as the "Sivas School of Industry Museum." The nearby section, which had formerly been used as a blacksmith workshop, now functions as the "Sivas Archaeology Museum." This transformation process reveals the importance of preserving historic structures while adapting them to contemporary needs in terms of sustaining and safeguarding cultural heritage.

The adaptive reuse of the Industrial School from a vocational training center to a prison, and then to a museum, reveals that it holds different layers of significance in everyone's collective memory. Similarly, the re-functioning of the blacksmith workshop as the Sivas Archaeology Museum has created a significant opportunity to showcase the region's rich history and cultural heritage. The use of these two companies as museums has both ensured the physical preservation of the structures and allowed the community to connect with its past.

The study discusses the architectural and social significance of these structures during the Ottoman modernization period, their transformation processes in the Republican era, and their roles within today's understanding of museology. In addition, the contributions of adaptive reuse practices to social memory, cultural identity, and urban memory are evaluated, while the potential for implementing visitor-oriented and participatory museology approaches in these buildings is emphasized. Thus, the study presents an important example not only of preserving historic buildings but also of sustaining them through new functions.

Keywords: Sivas School of Industry, Sivas Archaeology Museum, adaptive reuse, cultural heritage, museology, social memory

EXAMPLE

SİVAS SANAYİ MEKTEBİ MÜZESİ ve ARKEOLOJİ MÜZESİ'NİN YENİDEN İŞLEVLENDİRİLMESİ

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Özet

Bu bildiri, Sivas Sanayi Mektebi ile yakınında yer alan eski demircilik atölyesinin müze işleviyle yeniden kullanıma kazandırılmasını tarihsel, mimari ve toplumsal boyutları çerçevesinde incelemektedir. 1902 yılında Sultan II. Abdülhamid döneminde inşa edilen Sivas Sanayi Mektebi, Osmanlı Devleti'nin modernleşme ve sanayileşme politikalarının mekânsal düzlemdeki yansımalarından biri olarak değerlendirilmekte; özellikle kimsesiz çocuklara mesleki beceri kazandırmak amacıyla kurulmuş olması bakımından dönemin eğitim ve toplumsal politika anlayışını yansıtan önemli bir yapı olarak öne çıkmaktadır.

Zaman içerisinde farklı işlevlerle kullanılan yapı, Cumhuriyet döneminde de varlığını sürdürmüş; 2019 yılında tamamlanan kapsamlı restorasyon çalışmaları sonrasında "Sivas Sanayi Mektebi Müzesi" olarak yeniden hizmete açılmıştır. Yapının yakınında bulunan ve geçmişte demircilik atölyesi olarak kullanılan bölüm ise günümüzde "Sivas Arkeoloji Müzesi" olarak işlev görmektedir. Bu dönüşüm süreci, tarihî yapıların korunarak çağdaş ihtiyaçlara uyarlanmasının, kültürel mirasın sürekliliği ve yaşatılması açısından taşıdığı önemi ortaya koymaktadır.

Sanayi Mektebi'nin önce mesleki eğitim yuvası, ardından cezaevi olarak kullanılması ve sonrasında müzeye dönüştürülmesi, yapının toplumsal hafızada farklı katmanlara sahip olduğunu göstermektedir. Benzer şekilde, demircilik atölyesinin Sivas Arkeoloji Müzesi olarak yeniden işlevlendirilmesi, bölgenin zengin tarihi ve kültürel mirasının sergilenmesi için önemli bir fırsat oluşturmuştur. Bu iki yapının müze olarak kullanılması, hem yapıların fiziksel olarak korunmasını sağlamış hem de toplumun geçmişiyle bağ kurmasına olanak tanımıştır.

Çalışmada, bu yapıların Osmanlı modernleşme dönemindeki mimari ve toplumsal anlamı, Cumhuriyet dönemindeki dönüşüm süreçleri ve günümüz müzecilik anlayışı içerisindeki işlevleri ele alınmaktadır. Ayrıca yeniden işlevlendirme uygulamalarının toplumsal hafıza, kültürel kimlik ve kent belleği üzerindeki katkıları değerlendirilmekte; ziyaretçi odaklı ve katılımcı müzecilik yaklaşımlarının söz konusu yapılarda uygulanma potansiyeli vurgulanmaktadır. Böylece çalışma, tarihî yapıların yalnızca korunması değil, aynı zamanda yeni işlevlerle yaşatılması bağlamında önemli bir örnek sunmaktadır.

Anahtar Kelimeler: Sivas Sanayi Mektebi, Sivas Arkeoloji Müzesi, yeniden işlevlendirme, kültürel miras, müzecilik, toplumsal hafıza

EXAMPLE

TEKSTİL BOYAMACILIĞINDA KULLANILAN RUBİA TİNCTORUM L.'DE TOPRAK, BİTKİ BESLEME VE BOYA KALİTESİ ARASINDAKİ İLİŞKİLERİN DEĞERLENDİRİLMESİ: MEVCUT DURUM VE ARAŞTIRMA BOŞLUKLARI

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ÖZET

Rubia tinctorum L. (kökboya), içerdiği başlıca antrakinon türevleri (özellikle alizarin ve purpurin) nedeniyle tarihsel süreçte en önemli doğal kırmızı boya bitkilerinden biri olmuş ve tekstil boyamacılığında geniş kullanım alanı bulmuştur. Sentetik boyarmaddelerin çevresel ve toksik etkilerine yönelik artan farkındalık, kökboya gibi doğal kaynaklara olan ilgiyi yeniden artırmış ve bu bitkinin sürdürülebilir üretim sistemlerindeki potansiyelini ön plana çıkarmıştır. Mevcut çalışmalar, kökboya üzerine yapılan araştırmaların büyük ölçüde boya kimyası, tekstil uygulamaları ve antrakinon bileşiklerinin izolasyonu üzerine yoğunlaştığını; buna karşın toprak–bitki ilişkileri ve besin elementi yönetiminin sınırlı düzeyde ele alındığını göstermektedir. Bu çalışmanın amacı, tekstil boyamacılığında değerlendirilen Rubia tinctorum L.'de toprak özellikleri ve besin elementi yönetiminin boya kalitesi ile ilişkisini mevcut literatür çerçevesinde bütüncül olarak değerlendirmek ve bu alandaki araştırma boşluklarını ortaya koymaktır. Bitkinin derin, iyi drene olmuş, humusça zengin ve kireçli-tınlı topraklarda iyi geliştiği; ılıman ve yarı kurak koşullara adapte olabildiği ve tuzluluğa belirli düzeyde tolerans gösterdiği bildirilmektedir. Besin elementleri yönetimi açısından mevcut bulgular, özellikle azot ve potasyum uygulamalarının kök verimi ve toplam antrakinon içeriği üzerinde belirleyici olduğunu ortaya koymaktadır. Bununla birlikte, gübreleme uygulamalarının bitkinin sekonder metabolit profili üzerindeki etkilerine dair sınırlı sayıda çalışmada ele alınmıştır. Bu bağlamda, kökboya bitkisi üzerine mevcut literatür güçlü bir tarihsel ve tekstil boyamacılığına dayalı bilgi birikimi sunmakla birlikte, toprak özellikleri, besin elementi yönetimi ve boya kalitesi arasındaki etkileşimleri bütüncül olarak değerlendiren çalışmaların sınırlı olduğu görülmektedir. Bu nedenle, besin elementi yönetiminin yalnızca verim değil, aynı zamanda sekonder metabolit profili ve boya kalitesi üzerindeki etkilerini ortaya koyacak çok disiplinli yaklaşımlara odaklanmanın önemli katkılar sağlayabileceği düşünülmektedir.

Anahtar Kelimeler: Boya kalitesi, gübreleme, kökboya, Rubia tinctorum L., toprak verimliliği.

EXAMPLE

EVALUATION OF THE RELATIONSHIPS BETWEEN SOIL PROPERTIES, PLANT NUTRITION, AND DYE QUALITY IN RUBIA TINCTORUM L. USED IN TEXTILE DYEING: CURRENT STATUS AND RESEARCH GAPS

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ABSTRACT

Rubia tinctorum L. (madder), due to its main anthraquinone derivatives (especially alizarin and purpurin), has historically been one of the most important natural red dye plants and has found widespread use in textile dyeing. Increased awareness of the environmental and toxic effects of synthetic dyes, has revived interest in natural resources like madder, highlighting its potential in sustainable production systems. Current studies indicate that research on madder dye largely focuses on dye chemistry, textile applications, and the isolation of anthraquinone compounds. On the other hand, soil-plant relationships and nutrient management are addressed to a limited extent. This review examines the relationship between soil properties, nutrient management and dye quality in Rubia tinctorum L., which is used in textile dyeing, within the framework of the current knowledge and to reveal research gaps in this area. It has been reported that plant grows well in deep, well drained, humus rich and calcareous loamy soils. It can also adapt to temperate and semi-arid conditions and shows a certain level of tolerance to salinity. Regarding nutrient management, current findings indicate that in particular nitrogen and potassium applications have decisive influence on root yield and total anthraquinone content. However, the effects of fertilization practices on the secondary metabolite profile of the plant have been addressed in a limited number of studies. In this context, while the existing literature on madder plants offers a strong historical and textile dyeing-based body of knowledge, studies that holistically evaluate the interactions between soil properties, nutrient management, and dye quality are limited. Therefore, it is believed that focusing on multidisciplinary approaches that reveal the effects of nutrient management not only on yield but also on the secondary metabolite profile and dye quality could make significant contributions.

Keywords: Dye quality, fertilization, madder, Rubia tinctorum L., soil fertility.

EXAMPLE

Effects of Aerobic Exercise on Serum Myokine Levels in Patients with Ischemic Stroke

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AIM: Myokines are thought to be effective in combating cancer, diabetes, cardiovascular, and neurodegenerative diseases, and may also serve as useful biomarkers for monitoring the type and amount of exercise needed for prescribing exercise regimens.This study investigated the effects of aerobic exercise on physical recovery and myokine levels (irisin, brain-derivedneurotrophic factor [BDNF], interleukin-15 [IL-15], and myonectin) in patients with ischemic stroke.

METHODS: Of the 81 stroke patients who participated in the study, 41 were enrolled in a structured aerobic exercise program consisting of 45-minute sessions, three times per week. The remaining 40 patients were followed with an exercise program ofsimilar duration to be performed individually at home. Blood samples were collected from participants before and aftercompleting the exercise program, and sera were obtained. Serum myonectin, BDNF, IL-15, and irisin levels were measured using commercial kits according to the Enzyme-Linked Immunosorbent Assay (ELISA) method.

RESULTS: The findings revealed significant changes in myokine levels in the group participating in the aerobic exercise program compared to baseline. In this group, serum myonectin, BDNF, and IL-15 levels showed significant increases after the exercise program ($p<0.05$), whereas irisin levels significantly decreased ($p<0.05$). In the home exercise group, only myonectin levels increased significantly after the exercise program ($p<0.05$).

CONCLUSION: This study demonstrated that participation in a structured aerobic exercise program led to significant changesin myokine levels and meaningful improvements in physical functional recovery. In contrast, the home-based program had a lesser effect on both myokine levels and functional improvements. These results suggest that structured aerobic exercise programs are more effective in terms of both biochemical and functional outcomes.

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Keywords: ischemic stroke, myokine, aerobic exercise

EXAMPLE

Effect of URB597 on Kidney Damage in Sepsis Model Induced by Cecal Ligation and Puncture

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AIM: It has been shown that endocannabinoid levels in serum and renal tissue are altered in renal injury and this change iscorrelated with BUN and creatinine levels. Several studies in in vivo kidney injury models have demonstrated the potential of FAAH inhibition to reduce kidney injury and inflammation. In light of this information, in this study we will investigate the protective effect of the FAAH inhibitor URB597 on the kidney in a sepsis model created by cecal ligation and puncture (CLP).

METHODS: In the study, 40 male Sprague Dawley rats will be divided into 4 groups (Sham-control, CLP, CLP+URB597 0.3mg/kg, CLP+URB597 0.6 mg/kg) with 10 rats in each group. The cecum of CLP-treated rats was ligated and puncture was performed with a needle. Two different doses of URB597 (0.3 and 0.6 mg/kg) were administered intraperitoneally to the treatment groups immediately after CLP. Animals were sacrificed 24 hours after CLP procedure. Biochemical, histological and immunohistochemical examinations were performed on the serum and kidneys of the animals.

RESULTS: Increased levels of kidney injury biomarkers BUN, creatine, neutrophil gelatinase-associated lipocalin (NGAL), kidney injury molecule-1 (KIM-1) and proinflammatory cytokines tumor necrosis factor alpha (TNF-α) and interleukin 1 beta (IL-1β) in the sera of rats with CLP administration were significantly reduced by URB597 administration. Increased levels of TLR-4 and phosphorylated NF-κB (p65), p-IκB-α, tumor necrosis factor alpha (TNF-α), interleukin 1 beta (IL-1β), interleukin 6 (IL-6),caspase-3, caspase-8 immunoreactivity and histopathological damage in the kidney with CLP administration were reduced byURB597 administration.

EXAMPLE

CONCLUSION: In this study, it was concluded that URB597 administration at both doses (0.3 mg/kg and 0.6 mg/kg) showed aprotective effect by reducing inflammation and kidney damage induced in the experimental sepsis model.

This study was supported by Yozgat Bozok University BAP unit (project no: TÇD-2025-1688.

Keywords: Sepsis, Acute Kidney Injury, FAAH, URB597, Endocannabinoid

EXAMPLE

TARIMSAL İŞLETMELERDE ENERJİ MALİYETLERİNİN AZALTILMASINDA GÜNEŞ ENERJİSİ SİSTEMLERİNİN ROLÜ

THE ROLE OF SOLAR ENERGY SYSTEMS İN REDUCİNG ENERGY COSTS İN AGRİCULTURAL ENTERPRİSES

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ÖZET

Tarımsal işletmelerin üretim kapasitesinin artırılması, ürün çeşitliliğinin geliştirilmesi ve karlılığın yükseltilmesi birçok temel unsurda dönüşümü gerekli kılmaktadır. Bu dönüşümün önemli bileşenlerinden biri enerji ihtiyacının daha erişilebilir ve daha düşük maliyetle karşılanabilmesidir. Enerji giderlerinin azaltılması, işletmelerin sürdürülebilirliği açısından kritik önem taşımaktadır. Tarımsal üretimde kalite ve verim artışı büyük ölçüde makineleşmeye bağlı olduğu göz önüne alındığında makineleşmenin artması enerji talebinin yükselmesine neden olmaktadır.

Bu nedenle son yıllarda birçok tarımsal işletme enerji maliyetlerini düşürmek amacıyla yenilenebilir enerji kaynaklarından güneş enerjisinden yararlanmaya yönelmiştir. Güneş enerjisi sistemlerinin yaygınlaşmasıyla birlikte bu alana yönelik talep artmış, buna paralel olarak devlet tarafından sağlanan destek ve teşvik mekanizmaları da genişletilmiştir. Fosil kaynakların kıtlığı, zamanla tüketimi karşılayamayacak olması, küresel ısınmaya neden olması ve nükleer enerjinin ise Ukranya ve Japonya'da olduğu gibi tehlikeli yapısı bu tarz enerji kaynaklarını daha da önemli ve sürdürülebilir kılmaktadır.

Bu çalışma, tarımsal işletmelerde enerji maliyetlerinin azaltılmasında güneş enerjisi sistemlerinin rolünü incelemeyi amaçlamaktadır. Bu kapsamda, seçili tarım işletmelerinde güneş enerjisi sistemlerinin kurulum öncesi ve sonrası enerji giderleri ile güneş enerji sistemleri yatırım maliyetleri karşılaştırılmıştır. Elde edilen bulgular, güneş enerjisi sistemleri kullanımının enerji maliyetlerini önemli ölçüde azalttığını ve tarımsal işletmelerin ekonomik performansını olumlu yönde etkilediğini ortaya koymaktadır. Bu doğrultuda, tarımsal işletmelerde yenilenebilir enerji yatırımlarının yaygınlaştırılmasına yönelik politika ve uygulamalara katkı sunulması amaçlanmaktadır.

Anahtar Kelimeler: Tarımsal işletmeler, Güneş enerjisi, Enerji maliyetleri, Tarımsal makineleşme

EXAMPLE

ABSTRACT

Increasing the production capacity, enhancing product diversity, and improving the profitability of agricultural enterprises necessitate transformations across multiple fundamental components. One of the key elements of this transformation is the ability to meet energy demand in a more accessible and cost-effective manner. Reducing energy expenditures is of critical importance for the sustainability of these enterprises. Considering that improvements in quality and productivity in agricultural production largely depend on mechanization, the expansion of mechanization inevitably leads to an increase in energy demand.

In recent years, many agricultural enterprises have turned to renewable energy sources, particularly solar energy, in order to reduce energy costs. With the widespread adoption of solar energy systems, demand in this field has increased, and accordingly, government support and incentive mechanisms have been expanded. The scarcity of fossil resources, their inability to meet future consumption needs, their contribution to global warming, and the hazardous nature of nuclear energy, as evidenced in cases such as Ukraine and Japan, further highlight the importance and sustainability of such alternative energy sources.

This study aims to examine the role of solar energy systems in reducing energy costs in agricultural enterprises. Within this scope, energy expenditures before and after the installation of solar energy systems, as well as the investment costs of these systems, were compared in selected agricultural enterprises. The findings indicate that the use of solar energy systems significantly reduces energy costs and positively affects the economic performance of agricultural enterprises. In this context, the study aims to contribute to policies and practices aimed at promoting the adoption of renewable energy investments in agricultural enterprises.

Keywords: Agricultural enterprises, Solar energy, Energy costs, Agricultural mechanization.

EXAMPLE

MANUFACTURING AND PERFORMANCE ANALYSIS OF A REINFORCEMENT CONNECTION DEVICE DEVELOPED FOR ALTERNATIVE LOAD-PATH CONTINUITY IN REINFORCED CONCRETE STRUCTURES

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Abstract

The concept of progressive collapse, which arises due to the chain collapse mechanism resulting from unexpected loadings, local damages, and the loss of load-bearing elements for various reasons in reinforced concrete structural systems, has emerged in recent years as an important engineering problem and risk in terms of structural safety and structural continuity. In order to reduce this risk, the Tie Force analysis method, which is one of the progressive collapse analysis methods and is also included in the UFC 4-023-03 guideline, was adopted, and a mechanically based reinforcement apparatus prototype was developed to ensure reinforcement continuity, increase tensile force transfer capacity, and improve connection reliability. Due to the fact that conventional tie-wire applications may be insufficient especially under high tensile effects, may be affected by workmanship errors, and may not always provide the desired performance level in reinforcement connections, three different mechanical sleeve prototypes were designed for Ø16, Ø18, and Ø20 mm diameter deformed reinforcing bars. During the design process, the actual ribbed outer diameter measurements of the reinforcing bars were taken into consideration, the prototypes were modeled in the AutoCAD environment, and they were manufactured on a lathe using low-carbon solid steel material. External threads were formed at the ends of the reinforcing bars, while internal threads were formed on the inner surfaces of the sleeves, and mechanical interlocking was adopted in the connection region. The structural performance of the produced specimens was investigated through tensile tests, and the obtained data were evaluated. The experimental findings showed that the highest mechanical performance was obtained in the Ø16 mm diameter specimens, that the Ø18 mm specimens exhibited an acceptable level of behavior, and that the Ø20 mm specimens demonstrated relatively more limited performance. The occurrence of fractures not in the sleeve body but in the reinforcing bar section close to the connection region, at an inclination of approximately 40–45%, revealed that the developed system provided a favorable performance in terms of connection reliability. As a result, it is considered that the proposed prototype is an applicable engineering solution that strengthens reinforcement continuity, improves tensile force transfer, may constitute an alternative to conventional tie-wire applications, and has domestic production potential.

Keywords: Progressive collapse, reinforced concrete structures, tie force method, reinforcement continuity, mechanical coupler, tensile test

EARLY

Betonarme Yapılarda Alternatif Yük Yolu Sürekliliği İçin Geliştirilen Donatı Bağlantı Aparatının Üretimi ve Performans Analizi

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Özet

Betonarme yapı sistemlerinde beklenmeyen yüklemeler, yerel hasarlar ve çeşitli nedenlerle taşıyıcı eleman kayıpları sonucunda ortaya çıkan zincirleme çöküş mekanizmasına bağlı aşamalı göçme kavramı, yapı güvenliği ve yapısal süreklilik bakımından önemli bir mühendislik problemi ve riski olarak son yıllarda araştırmacıların karşısına çıkmaktadır. Söz konusu riskin azaltılmasına yönelik olarak aşamalı göçme analiz yöntemlerinden biri olan UFC 4-023-03 kılavuzunda da yer alan Bağ Kuvveti analiz yöntemi esas alınmış olup donatı sürekliliğinin sağlanması, çekme kuvveti aktarım kapasitesinin artırılması ve birleşim güvenilirliğinin iyileştirilmesi amacıyla mekanik esaslı bir donatı aparatı prototipi geliştirilmiştir. Geleneksel bağ teli uygulamalarının özellikle yüksek çekme etkileri altında yetersiz kalabilmesi, işçilik hataları ve donatı birleşimlerinde istenen performans düzeyini her durumda sağlayamaması nedeniyle Ø16, Ø18 ve Ø20 mm çaplı nervürlü donatılar için üç farklı mekanik manşon prototipi tasarlanmıştır. Tasarım sürecinde donatıların gerçek nervürlü dış çap ölçümleri dikkate alınmış, prototipler AutoCAD ortamında modellenmiş ve düşük karbonlu dolu çelik malzeme kullanılarak torna tezgâhında imal edilmiştir. Donatı uçlarına dış diş, manşon iç yüzeylerine ise iç diş açılarak birleşim bölgesinde mekanik kilitlenme esas alınmıştır. Üretilen numunelerin yapısal performansı çekme deneyleri ile incelenmiş ve elde edilen veriler değerlendirilmiştir. Deneysel bulgular, en yüksek mekanik performansın Ø16 mm çaplı numunelerde elde edildiğini, Ø18 mm numunelerin kabul edilebilir düzeyde davrandığını, Ø20 mm numunelerin ise görece daha sınırlı bir performans sergilediğini göstermiştir. Kopmaların manşon gövdesinde değil, birleşim bölgesine yakın donatı kesitinde yaklaşık %40-45 eğimle meydana gelmesi, geliştirilen sistemin bağlantı güvenilirliği açısından olumlu bir performans sunduğunu ortaya koymaktadır. Sonuç olarak önerilen prototipin, donatı sürekliliğini güçlendiren, çekme kuvveti aktarımını iyileştiren, geleneksel bağ teline alternatif oluşturabilecek ve yerli üretim potansiyeli taşıyan uygulanabilir bir mühendislik çözümü niteliğinde olduğu düşünülmektedir.

Anahtar Kelimeler: Aşamalı göçme, betonarme yapılar, bağ kuvveti yöntemi, donatı sürekliliği, mekanik manşon, çekme deneyi

EXAMPLE

SPIRULINA PLATENSIS İLE ZENGİNLEŞTİRİLMİŞ BİTKİSEL İÇECEK

A PLANT-BASED BEVERAGE ENRICHED WITH *SPIRULINA PLATENSIS*

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ÖZET

Yüzyıllardır birçok topluluk tarafından gıda olarak tüketilen *Spirulina* sp., son zamanlarda yeniden keşfedilmiştir. Çeşitli *Spirulina* türleri içerisinde mavi yeşil bir alg olan *Spirulina platensis* besin içeriğinin zengin olması ile dikkat çekmektedir. Bu çalışmada, yerel bir yağlı tohumdan bitkisel süt elde edilmesi, elde edilen bitkisel sütten fermente içecek üretilmesi, bu içeceğin fonksiyonel özelliğini artırmak için *S. platensis* ile zenginleştirilmesi ve son ürünün bazı fizikokimyasal özelliklerinin ortaya konması amaçlanmıştır. Bu amaçla yerel yağlı tohum olan Antep fıstığından bitkisel süt üretilmiştir. Üretilen bitkisel süte %1, %2 ve %4 oranlarında *S. platensis* ilave edilmiş ve probiyotik yoğurt kültürü ile fermente edilmiştir. Fermantasyon boyunca pH takip edilmiş ve pH 4.6'ya ulaştığında fermantasyon işlemi sonlandırılmıştır. Ardından fermente bitkisel içecekler depolama için 4°C'ye kaldırılmıştır. Depolamanın 1., 7., 14. ve 21. günlerinde örnekler alınarak analizler gerçekleştirilmiştir. *S. platensis* ilavesinin Antep fıstığı sütünden üretilen fermente bitkisel içeceklerin özelliklerine etkilerinin belirlenmesi için fizikokimyasal analizler yapılmıştır. Örneklerin pH (4,53-4,64), titrasyon asitliği (%0,65-%2,86), toplam kuru madde (%19,91-%22,89), toplam kül (%0,54-%0,85), su tutma kapasitesi (%50,35-%60,78) ve toplam fenolik madde içeriği (56,89 mg GAE/100g-186,21 mg GAE/100g) tespit edilmiştir. *S. platensis* ilaveli fermente Antep fıstığı sütü içeceği veganlar, vejetaryenler, kazein, laktoz gibi bileşenlere intoleransı ya da alerjisi olanlar ile sağlıklı beslenen tüm bireyler için alternatif bir ürün olma potansiyeline sahiptir.

Anahtar Kelimeler: Alerji, Antep Fıstığı, Fermantasyon, İntolerans, Probiyotik, *Spirulina platensis*

Teşekkür

Bu çalışma, Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (TÜBİTAK, 2209-A) tarafından [1919B012113094] numaralı proje kapsamında desteklenmiştir.

EXAMPLE

ABSTRACT

Spirulina sp. has been used as food for centuries by different populations and only rediscovered in recent years. Among the various species of *Spirulina*, the blue green alga *Spirulina platensis* has drawn more attention because it shows a high nutritional content. This study aimed to develop a plant-based milk from a local oilseed, produce a fermented beverage from this milk, enrich it with *S. platensis* to enhance its functional properties, and evaluate the physicochemical characteristics of the resulting product. Therefore, pistachio, a local oilseed, was selected as the raw material for producing plant-based milk. Plant-based milk was supplemented with *S. platensis* at concentrations of 1%, 2%, and 4% and subsequently fermented with a probiotic yogurt culture. The pH was monitored throughout the fermentation process, which was terminated when the pH reached 4.6. Following fermentation, the plant-based beverages were stored at 4°C. The samples were taken and analyzed on days 1, 7, 14, and 21 of storage. Physicochemical analyses were conducted to determine the effects of *S. platensis* addition on the properties of fermented plant-based pistachio beverages. The pH (4.53-4.64), titratable acidity (0.65%-2.86%), total dry matter (19.91%-22.89%), total ash (0.54%-0.85%), water-holding capacity (50.35%-60.78%), and total phenolic content (56.89 mg GAE/100g-186.21 mg GAE/100g) of the samples were determined. Fermented pistachio beverages enriched with *S. platensis* have the potential to serve as an alternative product for vegans, vegetarians, those with intolerances or allergies to components such as casein and lactose, and consumers following a healthy diet.

Keywords: Allergy, Pistachio, Fermentation, Intolerance, Probiotic, *Spirulina platensis*

Acknowledgment

This research was funded by [The Scientific and Technological Research Council of Türkiye (TÜBİTAK), 2209-A], grant number [1919B012113094].

EXAMPLE

ÜZÜM BAZLI GELENEKSEL BİR GIDA: ÜZÜM KÖFTESİ

A TRADITIONAL GRAPE-BASED FOOD: ÜZÜM KÖFTESİ

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ÖZET

Beslenmeye bağlı hastalıkların yaygınlaştığı son yıllarda insanların sağlıklı beslenmeye ilişkin bilinç düzeyleri yükselmiş, beraberinde tüketicilerin ilgisi doğal ürünlere yönelmiştir. Bu kapsamda geleneksel ürünler; kimyasal koruyucu içermemeleri, yerel hammaddelerden üretilmeleri ve doğal olmaları gibi özellikleriyle ön plana çıkmaktadır. Üzüm, bileşiminde bulunan çeşitli makro ve mikro besin öğeleri sayesinde sağlıklı beslenmede önemli bir yere sahiptir. Ayrıca yapısında bulunan sekonder metabolitlerin; antioksidan, antibakteriyel, antienflamatuvar ve antikarsinojen etkilerinden dolayı besleyici bir gıda olmanın ötesinde fonksiyonel bir besin olarak da tanımlanabilmektedir. Özellikle yüksek miktarda fenolik bileşenleri içermesi dolayısıyla kırmızı üzüm ve ürünlerine ilgi oldukça yoğundur. Üzüm ve ürünlerine olan ilgi nedeniyle antioksidan kapasitesi, fizikokimyasal ve mikrobiyolojik özellikleri ile insan sağlığı üzerine etkilerine ilişkin çalışmalar da artmaktadır. Üzüm sofralık olarak tüketilmekle birlikte kurutularak ya da işlenerek de tüketilmektedir. Geleneksel olarak ise yüzlerce yıldır üzümden pekmez, pestil, üzüm köftesi, orcik, üzüm peltesi, tarhana, bastık, bulama kesme, köfter, sucuk, tatlı vb. ürünler üretilmektedir. Üzüm köftesi, Türkiye'de çeşitli yörelerde benzer üretim yollarıyla üretilen ve kış boyu tüketilen geleneksel bir gıdadır. Geleneksel üretim için üzümün suyu çıkarılıp pekmez toprağı eklenerek bekletilmekte, tortu dibe çöktükten sonra üstte kalan berrak üzüm şırası kaynatılıp kıvamı koyulaştırılmaktadır. Koyulaşan şıraya irmik ya da bulgur ilave edilip pişirilmekte ve ardından tepsilere dökülerek 1 gece dinlendirilmektedir. Ertesi gün dilimlenen üzüm köfteleri güneşte kurutulmakta ve yıl boyu bez torbalarda muhafaza edilmektedir. Bu derlemede üzüm meyvesinin bazı özellikleri ve sağlığa yararlarına değinilmektedir. Bununla birlikte üzüm köftesinin geleneksel Türk mutfağındaki yerinin öne çıkarılması ve tanıtılması hedeflenmektedir.

Anahtar Kelimeler: Geleneksel gıda, üzüm, üzüm köftesi

Teşekkür

Bu çalışma, Muğla Sıtkı Koçman Üniversitesi, Sağlık Bilimleri Enstitüsü, Beslenme ve Diyetetik Ana Bilim dalı bünyesinde tamamlanan 'Farklı Kurutma Yöntemlerinin Arı Poleniyle Zenginleştirilmiş Üzüm Köftesinin Bazı Özelliklerine Etkisi' isimli yüksek lisans tezinden üretilmiş ve Muğla Sıtkı Koçman Üniversitesi Bilimsel Araştırma Projeleri (BAP) Birimi tarafından 22/134/01/3/5 numaralı proje ile desteklenmiştir.

EXAMPLE

ABSTRACT

In recent years, as nutrition-related diseases have become more prevalent, people's awareness of healthy eating has grown, resulting in a shift in consumer interest toward natural products. In this context, traditional products stand out for their characteristics, such as not containing chemical preservatives, being produced from local raw materials, and being natural. Grapes play an important role in a healthy diet because of their composition, particularly the variety of macro and micronutrients they provide. Furthermore, due to the antioxidant, antibacterial, anti-inflammatory, and anticarcinogenic effects of the secondary metabolites it contains, it can be defined not only as a nutritious food but also as a functional food. Red grapes and grape products are of great interest, particularly due to their high phenolic content. This interest has led to an increase in studies on their antioxidant capacity, physicochemical and microbiological properties, and their effects on human health. Grapes are consumed fresh as table grapes, but also dried or processed. Traditionally, for hundreds of years, grapes have been used to produce various sweet products. These products called as pekmez, pestil, üzüm köftesi, orcik, üzüm peltesi, tarhana, bastık, bulama kesme, köfter and sucuk. Üzüm köftesi is a traditional food consumed throughout the winter and produced using similar methods in various regions of Türkiye. In traditional production, grape juice is extracted and mixed with pekmez soil (clarifying soil) and allowed to stand. After the sediment settles at the bottom, the clarified grape must remain on top and boil until it reaches a thickened consistency. Semolina or bulgur is added to the thickened grape juice and cooked, then poured into trays and left to rest overnight. The next day, the sliced üzüm köftesi is dried in the sun and stored in cloth bags throughout the year. This review discusses some properties and health benefits of the grapes and aims to highlight and promote the place of üzüm köftesi in traditional Turkish cuisine.

Keywords: Traditional foods, grape, üzüm köftesi

Acknowledgment

This study was derived from the master's thesis entitled 'The Effect of Different Drying Methods on Some Properties of Bee Pollen Enriched "Üzüm Köftesi"', completed at Muğla Sıtkı Koçman University, Institute of Health Sciences, Department of Nutrition and Dietetics. The study has been granted by Muğla Sıtkı Koçman University Research Support and Funding Office through Project Grant Number: (22/134/01/3/5).

EXAMPLE

EVALUATION OF PROCESS PERFORMANCE IN MICROALGAE-BASED WASTEWATER TREATMENT USING ARTIFICIAL INTELLIGENCE

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ÖZET

Artan nüfus ve endüstriyel faaliyetler sonucunda oluşan atıksuların sürdürülebilir yöntemlerle arıtılması günümüzde önemli çevresel sorunlardan biri haline gelmiştir. Mikroalg tabanlı biyolojik arıtım sistemleri, besin maddelerini giderme kapasitesi, karbon dioksit tüketimi ve değerli biyokütle üretimi gibi avantajları sayesinde son yıllarda dikkat çeken alternatif teknolojiler arasında yer almaktadır. Bununla birlikte, mikroalg kültivasyon süreçleri; ışık şiddeti, sıcaklık, pH, besin konsantrasyonu ve hidrodinamik koşullar gibi çok sayıda parametrenin etkileşimine bağlı olarak karmaşık bir yapıya sahiptir. Bu nedenle proses performansının doğru şekilde izlenmesi ve tahmin edilmesi önemli bir araştırma alanı oluşturmaktadır.

Bu çalışmada, mikroalg tabanlı atıksu arıtım sistemlerinde proses performansının değerlendirilmesi amacıyla yapay zekâ ve makine öğrenmesi yaklaşımlarının kullanım potansiyeli incelenmiştir. Çalışma kapsamında, mikroalg büyümesi ve besin maddesi giderimi üzerinde etkili olan temel parametreler ele alınmış ve bu parametrelerin biyokütle üretimi ile arıtım verimi üzerindeki ilişkileri veri temelli modelleme yaklaşımıyla değerlendirilmiştir. Özellikle kimyasal oksijen ihtiyacı (COD), azot ve fosfor giderimi gibi temel arıtım parametrelerinin tahmin edilmesinde makine öğrenmesi algoritmalarının sağlayabileceği avantajlar tartışılmıştır.

Elde edilen bulgular, yapay zekâ tabanlı modellerin mikroalg tabanlı arıtma sistemlerinde proses performansının izlenmesi, optimizasyonu ve karar destek mekanizmalarının geliştirilmesi açısından önemli bir potansiyele sahip olduğunu göstermektedir. Bu yaklaşımın, sürdürülebilir atıksu yönetimi ve mikroalg tabanlı biyoproseslerin verimli şekilde işletilmesine katkı sağlayabileceği değerlendirilmektedir.

Anahtar Kelimeler: Mikroalg, atıksu arıtımı, yapay zekâ, makine öğrenmesi, proses optimizasyonu

ABSTRACT

The increasing population and industrial activities have led to a significant rise in wastewater generation, making sustainable treatment technologies increasingly important. Microalgae-based biological treatment systems have gained considerable attention in recent years due to their ability to remove nutrients, capture carbon dioxide, and produce valuable biomass. However, microalgae cultivation processes are complex systems influenced by multiple interacting parameters such as light intensity, temperature, pH, nutrient concentration, and hydrodynamic conditions. Therefore, monitoring and accurately predicting process performance remain key challenges in microalgae-based wastewater treatment systems.

In this study, the potential application of artificial intelligence and machine learning approaches for evaluating the process performance of microalgae-based wastewater treatment systems is investigated.

EXAMPLE

The study focuses on key operational parameters affecting microalgal growth and nutrient removal efficiency, and examines the relationships between these parameters and treatment performance using data-driven modeling approaches. In particular, the potential of machine learning algorithms to predict important treatment indicators such as chemical oxygen demand (COD), nitrogen, and phosphorus removal efficiencies is discussed.

The findings highlight that artificial intelligence-based models offer significant potential for improving process monitoring, optimization, and decision-support systems in microalgae-based wastewater treatment technologies. Such approaches may contribute to the development of more efficient and sustainable wastewater management strategies while enhancing the operational performance of microalgal bioprocesses.

Keywords: Microalgae, wastewater treatment, artificial intelligence, machine learning, process optimization

EXAMPLE

BEYOND THE CLASSROOM: PUBLİC SCHOOL TEACHERS' LİVED EXPERİENCES İN HANDLİNG ADVİSORY CLASSES

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Abstract: The study explored the lived experiences of public school teachers handling advisory classes within the Division of Cebu City. A descriptive phenomenology design was used, involving twelve (12) teachers with varied years of teaching and advisory experiences to unveil the essence of their roles beyond instructions. In-depth interviews using a semi-structured interview guide were conducted to gather data, which were analyzed thematically following Colaizzi's seven-step approach. The study's results revealed five central themes: (1) *carrying the weight of multiple responsibilities, (2) fostering deep connections and emotional bonds, (3) promoting resilience and adaptability despite unending challenges, (4) finding purpose and fulfillment beyond responsibilities, and (5) evolving identities as mentors and leaders.* These central themes revealed that the work of a class adviser encompasses not only supervision but also moral support, emotional care, and administrative tasks. Despite the challenges they have experienced, teachers still maintain a positive outlook on their role, as it has strengthened their sense of purpose, fulfillment, and professional growth in molding their students. Moreover, the study concludes that teaching advisory classes in a public school setting is both transformative and demanding, shaping teachers into mentors and leaders who remain resilient amid ongoing challenges. However, the study acknowledged specific limitations, including a small sample size, a solely qualitative method, and a limited scope. Thus, future studies are encouraged to adopt a quantitative or mixed-methods approach to attract more participants, elicit diverse responses, and foster a deeper exploration of findings, thereby enabling a deeper understanding of the worldview of class advisers.

Keywords: *Lived Experiences, Public School Teachers, Advisory Classes, Qualitative*

EXAMPLE

"MULTIFUNCTIONAL ROLES OF *TRICHODERMA SPP.* IN SUSTAINABLE AGRICULTURE, BIOTECHNOLOGY, AND ENVIRONMENTAL MANAGEMENT"

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ABSTRACT

The genus *Trichoderma* comprises a diverse group of free-living filamentous fungi belonging to the family Hypocreaceae and is ubiquitously distributed across a wide range of ecological habitats, including agricultural soils, plant rhizosphere, decaying organic matter, and composts. Owing to their rapid growth, high reproductive capacity, and remarkable metabolic adaptability, *Trichoderma* species are among the most frequently isolated and ecologically competitive fungi in terrestrial ecosystems. These characteristics enable them to efficiently colonize diverse substrates and interact dynamically with plants, microorganisms, and environmental factors. Over the past few decades, *Trichoderma spp*. have gained considerable attention due to their multifunctional roles as biological control agents, plant growth promoters, and producers of industrially important enzymes. Several species exhibit strong antagonistic activity against a broad spectrum of plant pathogenic fungi through mechanisms such as competition for nutrients and space, mycoparasitism, production of antifungal metabolites, and induction of host plant defense responses. In addition to disease suppression, *Trichoderma spp*. establish beneficial associations with plant roots, leading to enhanced nutrient uptake, improved root architecture, and increased tolerance to biotic and abiotic stresses. Beyond agriculture, *Trichoderma spp.* represent key microbial platforms in industrial biotechnology, particularly for the large-scale production of cellulases and other lingo-cellulolytic enzymes essential for biomass conversion and bio-based industries. Furthermore, their resilience to toxic compounds and ability to degrade complex organic materials make them promising candidates for environmental applications, including bioremediation and waste management. Given these diverse functional attributes, this review aims to provide an integrated overview of the biological mechanisms, agricultural relevance, industrial applications, and environmental significance of *Trichoderma spp.,* highlighting recent advances and future perspectives within the framework of applied microbiology and biotechnology.

Keywords: *Trichoderma spp*.; Biocontrol agents; Industrial biotechnology; Environmental sustainability; Plant growth promotion.

EXAMPLE

A COMPARATIVE ANALYSIS OF PALPUS LABIALIS MORPHOLOGY IN MICROLEPIDOPTERA FAMILIES

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Abstract

Within the class Insecta, the order Lepidoptera is the second most diverse insect order after Coleoptera. These insects, remarkable for the colors and patterns on their wings, are among the most studied insect groups. In addition to being one of the most sensitive indicator groups for environmental change among insects, they have been brought to the forefront of climate crisis research in recent years due to their importance in pollination. Crucial to their role in feeding and pollination, one of the most important and functional morphological structures in the head region of nectar-feeding adults is the palpus labialis (labial palpus). Located on both sides of the proboscis and generally consisting of three segments, these paired sensory organs—commonly referred to as labial palps—serve critical ecological functions such as olfaction, touch, pheromone detection, and mechanical protection of the proboscis during feeding. The shape and scaling of the labial palps, along with their size and orientation, are among the most fundamental taxonomic characters used to distinguish families and genera in Lepidoptera systematics. In this study, the labial palp morphology of a total of 10 species belonging to 5 microlepidoptera families found in Turkey was examined, and their micrographs are presented. The family Pterophoridae, which is distinguished from all other families by its divided, feather-like wings, also differs in its labial palp morphology. In this family, the labial palps are quite thin, delicate, and short compared to other families. In Pyralidae and Crambidae, they converge in front of the head and extend straight forward. In Crambidae in particular, this length is immediately noticeable when viewed dorsally. Another remarkable labial palp structure is observed in the family Gelechiidae. In this family, the labial palps have a thin and pointed structure extending backward over the head like a sickle.

Keywords: Pyralidae, Crambidae, Tortricidae, Gelechiidae, Pterophoridae, palpus labialis, morphology.

EXAMPLE

MIKROLEPIDOPTERA FAMİLYALARINDA PALPUS LABİALİS MORFOLOJİSİNİN KARŞILAŞTIRMALI ANALİZİ

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Özet

Insecta sınıfı içinde Lepidoptera (Kelebekler ve Güveler) takımı, Coleoptera'dan (Kınkanatlılar) sonra en yüksek çeşitliliğe sahip ikinci böcek takımıdır. Kanatlarındaki renk ve desenlerle dikkat çeken bu grup, en çok çalışılan böcek grupları arasında yer almaktadır. Böcekler arasında çevresel değişimlere karşı en hassas gösterge gruplarından biri olmalarının yanı sıra, tozlaşmadaki önemleri nedeniyle son yıllarda iklim krizi araştırmalarının da ön saflarına taşınmışlardır. Beslenme ve tozlaşmadaki rolleri açısından hayati öneme sahip olan, nektarla beslenen erginlerin baş bölgesindeki en önemli ve işlevsel morfolojik yapılardan biri palpus labialistir (labial palpus). Hortumun (proboscis) her iki yanında yer alan ve genellikle üç segmentten oluşan bu çift duyusal organlar —yaygın olarak labial palpler olarak adlandırılır— koku alma, dokunma, feromon tespiti ve beslenme sırasında hortumun mekanik olarak korunması gibi kritik ekolojik işlevleri yerine getirir. Labial palplerin şekli ve pullanma yapısı, boyutları ve yönelimleriyle birlikte, Lepidoptera sistematiğinde familyaları ve cinsleri ayırt etmek için kullanılan en temel taksonomik karakterler arasındadır. Bu çalışmada, Türkiye'de bulunan 5 mikrolepidoptera familyasına ait toplam 10 türün labial palp morfolojisi incelenmiş ve mikroskop görüntüleri sunulmuştur. Parçalı, tüy benzeri kanatlarıyla diğer tüm familyalardan ayrılan Pterophoridae familyası, labial palp morfolojisi bakımından da farklılık gösterir. Bu familyada labial palpler, diğer familyalara kıyasla oldukça ince, narin ve kısadır. Pyralidae ve Crambidae familyalarında ise başın önünde birleşir ve dümdüz ileriye doğru uzanırlar. Özellikle Crambidae familyasında bu uzunluk, üstten bakıldığında hemen göze çarpar. Bir diğer dikkate değer labial palp yapısı Gelechiidae familyasında gözlemlenmektedir. Bu familyada labial palpler, başın üzerinden geriye doğru bir orak gibi uzanan ince ve sivri bir yapıya sahiptir.

Anahtar Kelimeler: Pyralidae, Crambidae, Tortricidae, Gelechiidae, Pterophoridae, palpus labialis, morfoloji.

EXAMPLE

FINE STRUCTURE OF THE PROBOSCIS SENSILLA IN ARCHON APOLLINUS (HERBST, 1798) (LEPIDOPTERA): A SCANNING ELECTRON MICROSCOPY STUDY

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EXAMPLE

ÖZET

Papilionidae familyasının bir üyesi olan *Archon apollinus* (Herbst, 1798), monofag bir türdür. Larvaları *Aristolochia* L. cinsine ait konukçu bitkilerle beslenir. Kışı pupa evresinde geçirdikten sonra, erginler nisan ve mayıs aylarında ortaya çıkar. Tür univoltindir (yılda tek döl verir) ve yaklaşık iki haftalık bir uçuş süresine sahiptir. Habitatı temel olarak nadas alanları ve bozkırlardan oluşmaktadır. Habitat tahribatı ve iklim krizi, bu türün hayatta kalmasını tehdit eden başlıca faktörler arasındadır. Önemli bir endişe kaynağı, türün sıcaklık dalgalanmalarının neden olduğu larva konukçu bitkisindeki fenolojik kaymalara nasıl tepki vereceği ve yeni adaptasyonlar geliştirip geliştiremeyeceğidir. Erginlerin salgılarını algılayarak konukçu bitkileri bulmak için kullandıkları kemo- ve mekanoreseptif sensillalardaki potansiyel adaptasyonlar, türün çevreye uyum sağlaması ve hayatta kalması için kritik öneme sahiptir. Bu çalışmada, *A. apollinus*'un proboscisi üzerindeki sensillalar Taramalı Elektron Mikroskobu (SEM) kullanılarak incelenmiştir. Proboscis üzerinde farklı uzunluklarda sensilla chaetica tespit edilmiştir. Galeanın dış yüzeyinde iki tip sensilla basiconica gözlemlenmiştir: gözenekli s. basiconica ve gözeneksiz s. basiconica. Besin kanalı içinde sensilla basiconica seyrek olarak dağılmış olup, içbükey bir taban üzerinde yer alan oldukça uzun bir duyusal koniye sahiptir. Papilioninae alt familyasındaki *Iphiclides podalirius* L.'ta daha önce tanımlanmış olan sensilla coeloconica, *A. apollinus*'ta bulunmamaktadır. Yalnızca proboscisin distal bölgesinde yer alan sensilla styloconica, bazı diğer Parnassiinae üyelerinde bulunanlara benzer bir yapı sergilemiştir. Dikkat çekici bir şekilde, bu sensillalar Pieridae familyasında bulunan s. styloconica ile olan yapısal benzerlikleri nedeniyle de öne çıkmaktadır. Bu çalışma, *Archon apollinus*'taki proboscis sensillalarının ilk detaylı incelemesidir.

Anahtar Kelimeler: *Archon apollinus*, Papilionidae, proboscis, sensilla, taramalı elektron mikroskobu (SEM), morfoloji.

FINE STRUCTURE OF THE PROBOSCIS SENSILLA IN ARCHON APOLLINUS (HERBST, 1798) (LEPIDOPTERA): A SCANNING ELECTRON MICROSCOPY STUDY

ABSTRACT

Archon apollinus (Herbst, 1798), a member of the family Papilionidae, is a monophagous species. Its larvae feed on host plants of the genus *Aristolochia* L. After overwintering in the pupal stage, the adults emerge in April and May. The species is univoltine and has a flight period of approximately two weeks. Its habitat primarily consists of fallow fields and steppe areas. Habitat degradation and the climate crisis are among the leading factors threatening the survival of this species. A major concern is how the species will respond to phenological shifts in its larval host plant caused by temperature fluctuations, and whether it can develop new adaptations. Potential adaptations in the chemo- and mechanoreceptive sensilla—which the adults use to locate host plants by detecting their secretions—are of critical importance for their acclimation and survival. In this study, the sensilla on the proboscis of *A. apollinus* were investigated using Scanning Electron Microscopy (SEM). Sensilla chaetica of varying lengths were identified on the proboscis. Two types of sensilla basiconica were observed on the outer surface of the galea: porous s. basiconica and non-porous s. basiconica. Within the food canal, the sensilla basiconica were sparsely distributed and possessed a considerably long sensory cone situated on a concave base. Sensilla coeloconica, previously described in *Iphiclides podalirius* L. within the subfamily Papilioninae, were absent in *A. apollinus*. The sensilla styloconica, located exclusively in the distal region of the proboscis, exhibited a structure similar to those found in certain other Parnassiinae members. Notably, these sensilla also draw attention due to their structural resemblance to the s. styloconica found in the family Pieridae. This study represents the first detailed investigation of the proboscis sensilla in *Archon apollinus.*

Keywords: *Archon apollinus*, Papilionidae, proboscis, sensilla, scanning electron microscopy (SEM), morphology.

EXAMPLE

CHEMICAL COMPOSITION ANALYSIS OF *VISCUM ALBUM* (MISTLETOE) LEAF EXTRACTS FROM VARIOUS HOST PLANTS: ANTIBACTERIAL, ANTIOXIDANT, AND CYTOTOXIC PROPERTIES AND POTENTIAL USABILITY AS ORGANIC COMPONENT FOR THE SYNTHESIS OF CU-BASED HYBRID NANOFLOWER

Çağrı Çağlar SÖNMEZ

ABSTRACT

In the present study, the phenolic and flavonoid profiles, as well as the antioxidant and antimicrobial activities, of methanolic and aqueous extracts obtained from mistletoe plants parasitizing wild pear (1d, 2a), black pine, almond, wild plum, and pear trees were systematically investigated. Furthermore, the potential of these extracts as bioactive precursors in the synthesis of organic@inorganic hybrid nanoflowers (hNFs) was explored. Phytochemical compositions of host-specific mistletoe samples collected from different regions were characterized using Gas Chromatography/Mass Spectrometry (GC/MS) and High-Performance Liquid Chromatography (HPLC). Hexadecanoic acid (19.60%) was identified as the dominant compound in mistletoe from black pine, whereas 2-O-methyl-D-xylose (40.38%) was predominant in almond-derived samples. In contrast, mome inositol was determined as the principal component in mistletoe collected from wild plum (52.1%), pear (66.3%), wild pear 2a (67.75%), and wild pear 1d (72.18%). Antioxidant capacities were evaluated using DPPH•, ABTS•+, and FRAP assays in conjunction with total phenolic and flavonoid content analyses, revealing statistically significant variations depending on the host tree. The highest antioxidant and radical scavenging activities were observed in pear-derived samples, whereas the lowest activities were detected in wild plum and wild pear 1d, with no statistically significant difference between these two groups. Mistletoe extracts also exhibited antibacterial activity against the tested microorganisms. Functional groups, particularly hydroxyl (O–H) and amine (N–H), were found to play a critical role in facilitating hNF formation. The synthesis of hybrid nanoflowers was successfully achieved under neutral (pH 7.4) and alkaline (pH 9) conditions, while no formation occurred under acidic conditions (pH 5). Collectively, these findings demonstrate that mistletoe retains a high level of biological activity and highlight its potential as a sustainable and functional biomaterial for applications in nanotechnology and pharmaceutical development.

Keywords: Antibacterial, antioxidant, HPLC, GS/MS, flavonoid, mistletoe, phenolic.

EXAMPLE

STRESS, PHYSICAL ACTIVITY, AND HEALTH BEHAVIORS AMONG ADULT WOMEN

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Abstract

Aim: To investigate the correlations between stress and health behaviors, nutritional status, and body fat distribution among adult women. The study examines how psychosocial stress translates into biological risk through lifestyle factors. Methods: The study surveyed a large cohort of professionally active Polish women. Stress levels were operationalized through indicators of life satisfaction, suicidal ideation, and self-rated health. Anthropometric assessments focused on overall nutritional status (BMI) and abdominal fat distribution (WHR). Results: High levels of stress were significantly associated with increased health-risk behaviors, specifically physical inactivity and higher nicotine dependence. Conversely, highly stressed women reported lower consumption of alcohol and coffee. Regarding biological markers, high stress correlated with lower overall body mass but a higher waist-to-hip ratio, indicating a more hazardous pattern of fat distribution. Conclusions: Psychosocial stress acts as a significant determinant of anti-health lifestyle choices and adverse fat distribution in women. These findings suggest that chronic stress may lead to a deterioration of biological condition, negatively impacting long-term health, quality of life, and longevity.

Keywords: physical activity, health behaviors, stress, life satisfaction, Poland

EXAMPLE

INVESTIGATION OF THE EFFECTS OF TEMPERATURE ON DIFFERENT GROWTH STAGES IN COTTON

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Abstract

Cotton is a high economic value industrial plant grown primarily for fiber production, as well as for its oil and protein-rich seeds. Globally, cotton types known as "Upland" cotton, belonging to the species *Gossypium hirsutum*, are cultivated. Temperature plays a critical role in cotton production areas. The temperature requirement varies according to the phenological stages of the cotton. Temperature is a significant factor affecting the plant's germination, emergence, growth duration, vegetative and generative development stages, yield potential, and fiber quality characteristics. Cotton development can be predicted using Growing Degree Days (GDD) values. GDD tracking provides the opportunity to monitor the total heat energy received by the plant, predict developmental stages, and manage the risks created by climate variability.

Seed germination is the most critical period, and an accumulation of approximately 50-60 GDD (°C) is required for the seed to emerge above the soil surface. While warm conditions support vigorous growth, development is delayed at temperatures below 12-15°C, increasing the risk of cold damage to the cotton. Excessively high temperatures inhibit germination and reduce seedling development. Therefore, determining appropriate temperature ranges that support healthy plant development is very important. Temperature affects the periods and durations of squaring, flowering, boll formation, and boll opening following germination and emergence, and extreme temperatures are encountered during these stages. The plant is highly sensitive to temperatures above 32°C during this period; extreme temperatures above 35°C cause a reduction in leaf area, leading to a decrease in photosynthetic capacity. There is a negative relationship between excessively high temperatures and yield during flowering and early boll development. The pollen quality of plants exposed to heat stress decreases, causing flower and boll shedding, which results in yield loss. The inability of the cotton to meet its water requirement during this period can further exacerbate this stress. Boll development in cotton begins at 850-950 GDD, and cotton fibers develop inside the protective boll rind. The quality and quantity of the fiber produced at this stage directly affect the economic value of the product. Total heat accumulated toward the end of the season determines the fiber quality and the timing of boll opening. Bolls reach harvest maturity at 2200-2600 GDD. However, precise timing depends on the variety and growing conditions. A season that is only 1°C cooler than normal reduces the total GDD, causing the harvest to shift into critical rainfall periods.

Consequently, in cotton farming, precise monitoring of climate variability through GDD data in economic terms allows for better production planning by tracking cotton development stages.

Keywords: Cotton, thermal effect, GDD, harvest

EXAMPLE

PAMUKTA FARKLI BİTKİ GELİŞİM DÖNEMLERİNE GÖRE SICAKLIK ETKİSİNİN İNCELENMESİ

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EXAMPLE

Özet (Örnek)

Pamuk, lif üretimi başta olmak üzere yağ ve protein bakımından zengin tohumları için yetiştirilen ekonomik değeri yüksek bir endüstri bitkisidir. Dünya genelinde "Upland" pamuğu olarak bilinen *Gossypium hirsutum* türü pamuklar yetiştirilmektedir. Sıcaklık, pamuk ekim alanlarında kritik bir rol oynar. Sıcaklık ihtiyacı pamuğun fenolojik dönemlerine göre farklılık göstermektedir. Sıcaklık bitkinin çimlenme, çıkış, büyüme süresi, vejetatif ve generatif gelişme dönemleri, verim potansiyeli ve lif kalitesi özelliklerini etkileyen önemli bir faktördür. Büyüme Gün Derece değerleri (Growing Degree Days) ile pamuk gelişimi tahmin edilebilmektedir. GDD takibi, bitkinin aldığı toplam ısı enerjisini izleme, gelişim evrelerini öngörme ve iklim değişkenliğinin yarattığı riskleri yönetme imkânı sağlar.

Tohum çimlenmesi en kritik dönem olup tohumun toprak yüzeyine çıkabilmesi için yaklaşık 50-60 GDD (°C) birikimi gereklidir. Sıcak koşullar güçlü büyümeyi desteklerken, 12-15°C'nin altındaki sıcaklıklarda gelişme gecikir ve pamuğun soğuktan zarar görme riski artar. Aşırı yüksek sıcaklıklar çimlenmeyi engeller ve fide gelişimini azaltır. Bu nedenle sağlıklı bitki gelişimini destekleyen uygun sıcaklık aralıklarını belirlemek çok önemlidir. Çimlenmeyi ve çıkışı takip eden taraklanma, çiçeklenme, koza oluşturma ve koza açma dönemleri ve sürelerine sıcaklık etki etmektedir ve bu dönemlerde ekstrem sıcaklıklara rastlanmaktadır. Bitkinin bu dönemde 32ºC üzerindeki sıcaklıklara oldukça hassas olduğu, 35°C üzerindeki ekstrem sıcaklıklar yaprak alanını daraltarak fotosentez kapasitesinin düşmesine neden olmaktadır. Çiçeklenme ve erken koza gelişiminde aşırı yüksek sıcaklıklar ile verim arasında olumsuz bir ilişki vardır. Sıcaklık stresine maruz kalan bitkilerin polen kalitesi düşer ve çiçek-koza silkmesine neden olarak verim kaybı oluşur. Pamuğun bu dönemde su ihtiyacını karşılayamaması bu stresi daha da arttırabilmektedir. Pamukta koza gelişimi 850-950 GDD'de başlar ve pamuk lifleri koruyucu koza kabuğunun içinde gelişir. Bu aşamada üretilen lifin kalitesi ve miktarı, ürünün ekonomik değerini doğrudan etkiler. Sezon sonuna doğru biriken toplam ısı, lif kalitesini ve kozaların açılma zamanını belirler. 2200-2600 GDD'de ise kozalar hasat olgunluğuna ulaşır. Ancak kesin zamanlama çeşide ve yetiştirme koşullarına bağlıdır. Mevsimin normalden sadece 1°C daha soğuk geçmesi, toplam GDD'yi düşürerek hasadın kritik yağış dönemlerine sarkmasına neden olur.

Sonuç olarak pamuk tarımında ekonomik anlamda iklim değişkenliğinin GDD verileriyle hassas bir şekilde izlenmesiyle pamuk gelişim evreleri takip edilerek daha iyi bir üretim planlamasına olanak tanır.

Anahtar Kelimeler: Pamuk, ısı etkisi, GDD, hasat.

BAKLAGİL BAZLI NOODLE FORMÜLASYONLARINDA FONKSİYONEL LİFLERİN KIZARTMA SIRASINDA YAĞ EMİLİMİ VE TEKSTÜREL ÖZELLİKLER ÜZERİNE ETKİSİ

EFFECTS OF FUNCTIONAL FIBERS ON OIL UPTAKE AND TEXTURAL PROPERTIES IN LEGUME-BASED NOODLES DURING FRYING

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ÖZET

Baklagil bazlı unlar (mercimek ve nohut unu), yüksek protein ve diyet lifi içerikleri nedeniyle noodle üretiminde fonksiyonel alternatif hammaddeler olarak öne çıkmaktadır. Ancak gluten içermemeleri ve farklı nişasta–protein matrisi yapıları nedeniyle, özellikle kızartma sırasında artan yağ emilimi ve buna bağlı tekstürel bozulmalar önemli teknolojik zorluklar oluşturmaktadır. Bu çalışmada, baklagil bazlı noodle formülasyonlarına farklı fonksiyonel liflerin (inülin, β-glukan ve dirençli nişasta) ilavesinin kızartma sırasında yağ alımı, nem kaybı ve tekstürel özellikler üzerindeki etkileri incelenmiştir.

Bu kapsamda %50 baklagil unu içeren temel formülasyona %3, %6 ve %9 oranlarında fonksiyonel lif ilave edilerek noodle örnekleri hazırlanmıştır. Numuneler standart koşullarda (buharlama: 100 °C, 3 dk; kızartma: 170±5 °C, 2 dk) işlenmiştir. Yağ alımı Soxhlet yöntemi ile belirlenmiş, tekstürel özellikler tekstür profil analizi (TPA) ile ölçülmüş, ayrıca nem kaybı ve renk parametreleri (L*, a*, b*) değerlendirilmiştir.

Sonuçlar, kontrol örneğinde yağ alımının %18.6±1.2 olduğunu, fonksiyonel lif ilavesi ile bu değerin %13.4±0.9 (β-glukan), %14.1±1.0 (dirençli nişasta) ve %15.6±1.1 (inülin) seviyelerine düştüğünü göstermiştir ($p<0.05$). Nem kaybı kontrol grubunda %42±2 iken, lif içeren örneklerde %35–38 aralığında belirlenmiştir. Tekstürel analizlerde sertlik değerleri 3.2±0.3 N'den 4.1±0.4 N'ye yükselmiş, kırılganlık azalmış ve elastikiyet değerlerinde anlamlı artış gözlenmiştir ($p<0.05$). Renk analizinde lif ilavesi ile L* değerinde sınırlı bir azalma gözlenmiş, ancak ürünlerin kabul edilebilir renk aralığında kaldığı belirlenmiştir.

Elde edilen bulgular, fonksiyonel liflerin su bağlama kapasitesi ve jel oluşturma özellikleri sayesinde kızartma sırasında su kaybını sınırlayarak yağın ürün içerisine penetrasyonunu azalttığını

EXAMPLE

göstermektedir. Özellikle β-glukan ve dirençli nişasta içeren formülasyonlar, yağ alımının kontrolü ve tekstürel stabilitenin artırılması açısından daha etkili bulunmuştur.

Sonuç olarak, fonksiyonel lif ilavesi, baklagil bazlı noodle sistemlerinde kızartma sırasında yağ emilimini azaltmakta ve ürün kalitesini iyileştirmektedir. Bu yaklaşım, daha sağlıklı kızartılmış noodle ürünlerinin geliştirilmesi için endüstriyel olarak uygulanabilir bir strateji sunmaktadır.

Anahtar Kelimeler: Baklagil unu, fonksiyonel lif, yağ emilimi, kızartma, tekstür, noodle.

ABSTRACT

Legume-based flours (lentil and chickpea) have gained increasing attention as functional alternatives in noodle production due to their high protein and dietary fiber content. However, the absence of gluten and differences in starch–protein matrix structure lead to technological challenges, particularly increased oil uptake during frying and undesirable textural properties. This study aimed to evaluate the effects of different functional fibers (inulin, β-glucan, and resistant starch) on oil absorption, moisture loss, and textural properties of legume-based noodles during frying.

Noodle samples were prepared with 50% legume flour and supplemented with functional fibers at levels of 3%, 6%, and 9%. Samples were processed under standardized conditions (steaming at 100 °C for 3 min followed by frying at 170±5 °C for 2 min). Oil uptake was determined using Soxhlet extraction, while textural properties were analyzed by texture profile analysis (TPA). Moisture loss and color parameters (L*, a*, b*) were also evaluated.

Results showed that oil uptake in the control sample was 18.6±1.2%, which decreased significantly to 13.4±0.9% (β-glucan), 14.1±1.0% (resistant starch), and 15.6±1.1% (inulin) in fiber-enriched formulations ($p<0.05$). Moisture loss decreased from 42±2% in the control to 35–38% in fiber-containing samples. Texture analysis indicated that hardness increased from 3.2±0.3 N to 4.1±0.4 N, brittleness decreased, and elasticity improved significantly ($p<0.05$). Although a slight decrease in L* values was observed, all samples remained within acceptable color ranges.

The results suggest that functional fibers reduce oil uptake by limiting moisture loss and forming a protective matrix that restricts oil penetration during frying. Among the tested fibers, β-glucan and resistant starch demonstrated superior performance.

In conclusion, the incorporation of functional fibers effectively reduces oil uptake and improves product quality in legume-based fried noodles. This approach provides an industrially feasible strategy for developing healthier fried noodle products.

Keywords: Legume flour, functional fiber, oil uptake, frying, texture,

EXAMPLE

DÜŞÜK GLİSEMİK İNDEKSLİ NOODLE GELİŞTİRİLMESİNDE FONKSİYONEL BİLEŞENLER VE PROSES PARAMETRELERİNİN ETKİLEŞİMİ

INTERACTION OF FUNCTIONAL INGREDIENTS AND PROCESSING PARAMETERS IN THE DEVELOPMENT OF LOW GLYCEMIC INDEX NOODLES

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EXAMPLE

ÖZET

Düşük glisemik indeksli (GI) gıdalar, postprandiyal glukoz yanıtının kontrolü ve metabolik hastalık riskinin azaltılması açısından kritik öneme sahiptir. Bu çalışmada, buğday unu yerine mercimek ve nohut unu kullanılarak düşük GI özellikte noodle geliştirilmiş ve gluten eksikliğine bağlı yapısal zayıflıkların fonksiyonel bağlayıcı sistemler ve proses optimizasyonu ile giderilmesi amaçlanmıştır. Çalışma kapsamında %50–70 oranında baklagil unu içeren formülasyonlar hazırlanmış; bağlayıcı sistem olarak %1.0–2.0 hidroksipropil metilselüloz (HPMC), %0.5–1.0 ksantan gam ve %2.0–4.0 bezelye proteini kombinasyonları kullanılmıştır. Proses parametreleri olarak hamur nemi (%32–36), açma kalınlığı (1.2–1.5 mm), buharlama süresi (2–4 dk) ve kontrollü soğutma (4 °C, 30 dk) optimize edilmiştir.

Hamur reolojisi analizleri, baklagil bazlı sistemlerde gluten yokluğuna bağlı olarak elastik modülün önemli ölçüde azaldığını, ancak optimize bağlayıcı sistem ile viskoelastik davranışın kısmen geri kazanıldığını göstermiştir. Kontrol grubuna kıyasla hamur elastikiyeti başlangıçta %35 oranında düşerken, optimize sistemde bu kayıp %18 seviyesine indirgenmiştir ($p<0.05$). Tekstür profil analizinde sertlik 2.8±0.2 N'den 3.6±0.3 N'ye yükselmiş, elastikiyet 0.62±0.04'ten 0.78±0.03'e artmıştır. Pişme kaybı %8.5±0.6'dan %5.2±0.4'e düşürülerek ürün bütünlüğünün iyileştiği belirlenmiştir.

In vitro nişasta sindirilebilirlik analizlerinde hızlı sindirilebilir nişasta (RDS) fraksiyonu %62±2.1'den %41±1.8'e düşerken, dirençli nişasta (RS) oranı %6.5±0.7'den %14.2±1.1'e yükselmiştir ($p<0.05$). Bu değişim, protein–nişasta ve hidrokolloid–nişasta etkileşimleri ile nişasta granül erişilebilirliğinin azalmasına bağlanmıştır. Tahmini glisemik indeks (eGI) değerleri kontrol grubunda 72±3 iken, optimize formülasyonda 48±2 olarak hesaplanmıştır.

Sonuç olarak, fonksiyonel bileşenler ile proses parametrelerinin birlikte optimize edilmesi, baklagil bazlı noodle sistemlerinde hem yapısal performansı iyileştirmekte hem de glisemik yanıtı anlamlı

düzeyde düşürmektedir. Bu yaklaşım, düşük GI hedefli fonksiyonel noodle üretimi için hem bilimsel hem de endüstriyel açıdan uygulanabilir bir model sunmaktadır.

Anahtar Kelimeler: Düşük glisemik indeks, noodle, baklagil unu, hidrokolloid, nişasta sindirilebilirliği, fonksiyonel gıda.

ABSTRACT

Low glycemic index (GI) foods are of significant importance for controlling postprandial glucose response and reducing the risk of metabolic disorders. In this study, low-GI noodles were developed using lentil and chickpea flours as substitutes for wheat flour, and structural deficiencies caused by the absence of gluten were addressed through functional binder systems and process optimization. Formulations containing 50–70% legume flour were prepared, and binder systems consisting of 1.0–2.0% hydroxypropyl methylcellulose (HPMC), 0.5–1.0% xanthan gum, and 2.0–4.0% pea protein were evaluated. Process parameters including dough moisture (32–36%), sheet thickness (1.2–1.5 mm), steaming time (2–4 min), and controlled cooling (4 °C for 30 min) were optimized.

Rheological analyses indicated that the absence of gluten significantly reduced the elastic modulus of the dough systems, while the optimized binder system partially restored viscoelastic behavior. Compared to the wheat-based control, dough elasticity decreased by 35% initially but was improved to 18% loss after optimization ($p<0.05$). Texture profile analysis showed that hardness increased from 2.8±0.2 N to 3.6±0.3 N, while elasticity improved from 0.62±0.04 to 0.78±0.03. Cooking loss decreased significantly from 8.5±0.6% to 5.2±0.4%, indicating improved structural integrity.

In vitro starch digestibility analysis revealed a decrease in rapidly digestible starch (RDS) from 62±2.1% to 41±1.8%, while resistant starch (RS) increased from 6.5±0.7% to 14.2±1.1% ($p<0.05$). This shift was attributed to reduced starch accessibility due to protein–starch and hydrocolloid–starch interactions. The estimated glycemic index (eGI) decreased from 72±3 in the control sample to 48±2 in the optimized formulation.

In conclusion, the combined optimization of functional ingredients and processing parameters significantly improves both structural performance and glycemic response in legume-based noodle systems. This approach provides a scientifically robust and industrially applicable model for the development of low-GI functional noodles.

Keywords: Low glycemic index, noodle, legume flour, hydrocolloid, starch digestibility, functional food.

EXAMPLE

THE EFFECT OF DIFFERENT METHODS FOR TEACHING PELVIC FLOOR MUSCLE CONTRACTION ON ABDOMINAL AND PELVIC FLOOR MUSCLE ACTIVATION RESPONSE: BF-EMG ANALYSIS

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EXAMPLE

Abstract

Pelvic floor muscle training (PFMT) is one of the fundamental approaches used in the prevention and treatment of pelvic floor dysfunctions. During pelvic floor muscle contraction, abdominal muscles may physiologically co-activate with the pelvic floor; however, excessive abdominal activation may act as a compensatory strategy and impair proper muscle activation. Therefore, one of the main goals of PFMT is to reduce excessive abdominal compensation while maintaining muscle synergy.

The aim of this study was to investigate the effects of two different PFMT methods on pelvic floor muscle activation and abdominal muscle compensation.

A total of 32 women (mean age: 44.31 ± 5.69 years) were included. Participants were divided into two groups: verbal instruction (n=16) and digital vaginal palpation (DVP)-guided training (n=16), and a single-session PFMT was applied. Pelvic floor and transversus abdominis muscle activation were assessed before and after training using biofeedback electromyography (BF-EMG) (µV). Within-group analyses were performed using the Wilcoxon signed-rank test, and between-group comparisons were conducted using the Mann–Whitney U test.

In the DVP group, pelvic floor muscle activation significantly increased (p=0.034), while abdominal muscle activation decreased (p=0.019). In the verbal instruction group, no significant changes were observed in pelvic floor (p=0.379) or abdominal muscle activation (p=0.535). Between-group comparisons showed a significantly greater increase in pelvic floor muscle activation in favor of the DVP group (p=0.038), whereas no significant difference was found in abdominal muscle activation (p=0.127).

DVP is more effective than verbal instruction in teaching correct muscle contraction by increasing pelvic floor muscle activation and reducing abdominal activation. The significantly greater increase in pelvic floor muscle activation in the DVP group supports this finding. The absence of a difference in abdominal muscle activation between groups suggests that abdominal control may be more difficult to achieve and may be related to the synchronized contribution of the transversus abdominis. In other words, the results of this study suggest that training

delivered via DVP may be more effective in achieving correct muscle activation and highlight the importance of muscle synergy in PFMT.

This study was financially supported by TÜBİTAK (The Scientific and Technological Research Council of Turkey) 1002A Rapid Support Program (no: 224S541).

Keywords: Biofeedback, Electromyography, Pelvic Floor, Physiotherapy and Rehabilitation

EXAMPLE

FARKLI PELVİK TABAN KAS KONTRAKSİYONUNU ÖĞRETME YÖNTEMLERİNİN ABDOMİNAL VE PELVİK TABAN KAS AKTİVASYON CEVABI ÜZERİNE ETKİSİ: BF-EMG ANALİZİ

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Özet

Pelvik taban kas eğitimi (PTKE), pelvik taban disfonksiyonlarının önlenmesi ve tedavisinde uygulanan temel yaklaşımlardan biridir. Pelvik taban kas kontraksiyonu sırasında abdominal kaslar fizyolojik olarak pelvik tabana eşlik edebilir; ancak aşırı abdominal aktivasyon kompansatuar bir stratejiye dönüşerek doğru kas aktivasyonunu bozabilmektedir. Bu nedenle, PTKE'nin temel hedeflerinden biri kas sinerjisini korurken aşırı abdominal kompansasyonu azaltmaktır.

Bu çalışmanın amacı; PTKE'de kullanılan iki farklı yöntemin, pelvik taban kas aktivasyonu ve abdominal kas kompansasyonu üzerindeki etkisini incelemektir.

Çalışmaya yaş ortalaması 44.31 ± 5.69 yıl olan 32 kadın dahil edildi. Katılımcılar sözel eğitim (n=16) ve dijital vajinal palpasyon (DVP) ile eğitim (n=16) olmak üzere iki gruba ayrıldı ve tek seans PTKE uygulandı. Pelvik taban ve transversus abdominis kas aktivasyonu, eğitim öncesi ve sonrası biyofeedback elektromiyografi (BF-EMG) ile (µV) değerlendirildi. Grup içi analizde Wilcoxon, gruplar arası analizde Mann–Whitney U testi kullanıldı.

DVP grubunda eğitim sonrası pelvik taban kas aktivasyonu anlamlı olarak artarken (p=0.034), abdominal kas aktivasyonu azaldı (p=0.019). Sözel eğitim grubunda ise pelvik taban (p=0.379) ve abdominal kas aktivasyonunda (p=0.535) anlamlı değişiklik görülmedi. Gruplar arası karşılaştırmada pelvik taban kas aktivasyonu DVP grubu lehine anlamlı artış gösterirken (p=0.038), abdominal kas aktivasyonu açısından fark saptanmadı (p=0.127).

DVP, pelvik taban kas aktivasyonunu artırıp abdominal aktivasyonu azaltarak, sözel eğitime kıyasla doğru kas kontraksiyonunu öğretmede daha etkilidir. Pelvik taban kas aktivasyonundaki artışın DVP grubu lehine anlamlı bulunması bu görüşü desteklemektedir. Abdominal kas aktivasyonunda fark saptanmaması ise abdominal kontrolün daha zor kazanıldığını ve bunun transversus abdominusun senkronize katkısıyla ilişkili olabileceğini düşündürmektedir. Diğer bir deyişle; bu çalışma sonuçları; DVP ile verilen eğitimin doğru kas aktivasyonunun sağlanmasında daha etkili olabileceğini ve PTKE'de kas sinerjisinin önemini ortaya koymaktadır.

EXAMPLE

Bu çalışma, TÜBİTAK (Türkiye Bilimsel ve Teknolojik Araştırma Kurumu) 1002A Hızlı Destek Programı (no: 224S541) tarafından finansal olarak desteklenmiştir.
Anahtar Kelimeler: Biyofeedback, Elektromiyografi, Pelvik taban, Fizyoterapi ve Rehabilitasyon

EXAMPLE

COMPARISON OF TWO DIFFERENT ASSESSMENT METHODS IN TERMS OF SENSITIVITY TO TRAINING-INDUCED CHANGES IN PELVIC FLOOR MUSCLE STRENGTH: DIGITAL VAGINAL PALPATION AND PERINEOMETER

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EXAMPLE

Abstract

During the assessment of pelvic floor muscles (PFM), it is important to ensure correct muscle activation, to distinguish compensatory muscle use, and to objectively evaluate muscle performance. In clinical practice, muscle strength is frequently assessed using digital vaginal palpation (DVP), while methods such as perineometry, which provide quantitative data, are also utilized. Although the relationship between these methods has been demonstrated in the literature, there is no consistent evidence regarding whether they reflect changes in muscle contraction with similar sensitivity.

The aim of this study was to compare two different training methods (verbal instruction and training with digital vaginal palpation (DVP) in terms of their effects on changes in pelvic floor muscle (PFM) contraction strength, and to evaluate the sensitivity of two assessment methods DVP using the Modified Oxford Scale (MOS) and perineometric measurements in detecting these changes.

A total of 32 women with a mean age of 44.31 ± 5.69 years were included in the study. Participants were allocated into two groups: verbal instruction (n=16) and DVP-guided training (n=16). A single-session PFM contraction training was administered. PFM contraction strength was assessed before and after the intervention using MOS (0–5) and a perineometer. Change scores (ΔMOS and Δperineometer) were calculated for both methods. Only individuals with a baseline PFM contraction level of ≥2 according to MOS were included. Within-group pre–post differences were analyzed using the Wilcoxon signed-rank test, while between-group comparisons based on training methods were performed using the Mann–Whitney U test. Statistical significance was set at $p<0.05$.

An increase in muscle strength assessed by MOS was observed in 18.8% of participants, whereas this rate was 78.1% based on perineometric measurements. When pre- and post-training values were compared within each method, a statistically significant difference in change scores was found (Wilcoxon Signed-Rank Test, p=0.003). In comparisons based on

training methods, no statistically significant differences were found between the verbal instruction and DVP groups in terms of either ΔMOS (p=0.564) or Δperineometer (p=0.867). The interpretation of changes in PFM strength varied depending on the assessment method used. Perineometric measurements appeared to be more sensitive than MOS in detecting changes. However, no significant differences were observed between the two training methods in terms of changes measured by either MOS or perineometry. Although a single training session is not expected to produce a substantial increase in muscle strength, the findings suggest that correct muscle activation may have been achieved. Accordingly, while DVP remains valuable for qualitative assessment, the use of perineometric measurements is recommended for a more objective and sensitive evaluation of change.

This study was financially supported by TÜBİTAK (The Scientific and Technological Research Council of Turkey) 1002A Rapid Support Program (no: 224S541).

Keywords: Pelvic Floor, Digital Vaginal Palpation, Perineometer

EXAMPLE

PELVİK TABAN KAS KUVVETİNDE, EĞİTİM İLE MEYDANA GELEN DEĞİŞİME DUYARLILIK AÇISINDAN İKİ FARKLI DEĞERLENDİRME YÖNTEMİNİN KARŞILAŞTIRILMASI: DİJİTAL VAJİNAL PALPASYON VE PERİNEOMETRE

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Özet

Pelvik taban kaslarının (PTK) değerlendirilmesi sırasında doğru kas aktivasyonunun yapılması, kompansatuar kas kullanımının ayırt edilmesi ve kasın performansını objektif olarak değerlendirmek önemlidir. Klinik uygulamada, kas kuvveti sıklıkla dijital vajinal palpasyon (DVP) ile değerlendirilmekte, bunun yanında perineometre gibi sayısal veri sağlayan yöntemler de kullanılmaktadır. Literatürde bu yöntemler arasında ilişki gösterilmiş olmakla birlikte, kas kontraksiyonundaki değişimi benzer duyarlılıkta yansıtıp yansıtmadıkları konusunda tutarlı sonuçlar bulunmamaktadır.

Bu çalışmanın amacı; farklı iki eğitim yönteminin (sözel eğitim ile DVP eşliğinde verilen eğitimin) PTK kontraksiyon kuvvetindeki değişimi, değerlendirmede kullanılan DVP (Modifiye Oxford Skalası=MOS) ve perineometrik ölçümler açısından karşılaştırarak, bu iki yöntemin değişime olan duyarlılıklarını karşılaştırmaktır.Çalışmaya yaş ortalaması 44.31 ± 5.69 yıl olan 32 kadın dahil edildi. Katılımcılar sözel eğitim (n=16) ve DVP ile eğitim (n=16) olmak üzere iki gruba ayrıldı ve tek seans PTK kontraksiyon eğitimi uygulandı. Katılımcıların PTK kontraksiyonu, eğitim öncesi ve sonrası MOS (0–5) ve perineometre ile değerlendirildi. Her iki yöntem için değişim değerleri (ΔMOS ve Δperineometre) hesaplandı. Çalışmaya, MOS'a göre ≥2 düzeyinde PTK kontraksiyonuna sahip bireyler dahil edildi. Eğitim öncesi ve sonrası değişim değerlerinin değerlendirilmesinde Wilcoxon işaretli sıralar testi, eğitim yöntemlerine göre gruplar arası karşılaştırmalarda ise Mann-Whitney U testi uygulandı. İstatistiksel anlamlılık düzeyi $p<0.05$ olarak kabul edildi. MOS ile değerlendirilen kas kuvvetinde katılımcıların %18.8'inde artış saptanırken, perineometrik ölçümlerde bu oran %78.1 olarak gözlendi. İki ölçüm yöntemi de eğitim öncesi ve sonrası kendi içlerinde karşılaştırıldığında, elde edilen değişim değerleri arasında istatistiksel olarak anlamlı fark bulundu (Wilcoxon Signed Rank Test, $p=0.003$).Eğitim yöntemlerine göre yapılan analizlerde, sözel eğitim ve DVP grupları arasında hem ΔMOS ($p=0.564$) hem de Δperineometre ($p=0.867$) açısından istatistiksel olarak anlamlı fark yoktu.PTK kuvvetindeki değişimin yorumu, kullanılan değerlendirme yöntemine göre farklılık gösterdi. Perineometrik ölçümlerin, MOS'a

SAMPLE

kıyasla değişimi değerlendirmede daha duyarlı olduğu görülürken, eğitim yöntemleri arasında hem MOS hem de perineometrik ölçümlerde elde edilen değişim değerleri açısından anlamlı bir fark bulunmadı. Tek seanslık eğitimin kas kuvvetinde belirgin bir artış oluşturması beklenmemekle birlikte, elde edilen bulgular, doğru kas aktivasyonunun sağlanabildiğini düşündürmektedir. Bu sonuçlar doğrultusunda, DVP nitel değerlendirme açısından önemli olmakla birlikte, değişimin objektif ve duyarlı biçimde ortaya konulabilmesi için perineometrik ölçümlerin kullanımı önerilmektedir.

Bu çalışma, TÜBİTAK (Türkiye Bilimsel ve Teknolojik Araştırma Kurumu) 1002A Hızlı Destek Programı (no: 224S541) tarafından finansal olarak desteklenmiştir.

Anahtar Kelimeler: Pelvik taban, Dijital Vajinal Palpasyon, Perineometre

EXAMPLE

KİTOSAN KAPLAMALARININ ERİNGİ MANTARI (Pleurotus eryngii)'NDA MODİFİYE ATMOSFER KOŞULLARINDA RENK VE GAZ BİLEŞİMİ ÜZERİNE ETKİLERİ

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ÖZET

Mevcut çalışmada, modifiye atmosfer koşullarının ve yenilebilir kaplama malzemesi olan kitosan uygulamasının, Pleurotus eryngii mantarının hasat sonrası fizyolojisi üzerine etkileri araştırılacaktır. P. eryngii miseli, Sylvan Tarım Ürünleri Sanayi ve Tic. Ltd. Şti. (Kocaeli, Türkiye) aracılığıyla yurt dışından

ticari misel olarak temin edilmiştir. Yetiştirme denemeleri, Van Yüzüncü Yıl Üniversitesi Mantar Araştırma ve Uygulama Merkezi'ne ait, çevresel parametreleri kontrol edilebilen ranza sistemli üretim odalarında gerçekleştirilmiştir.

Denemelerde meşe talaşı ana yetiştirme materyali olarak kullanılırken, alçı ve buğday kepeği katkı maddesi olarak eklenmiştir. Yetiştirme ortamı, %90 meşe talaşı, %9 buğday kepeği ve %1 alçı içerecek şekilde hazırlanmıştır. Bu karışım, homojen olarak karıştırılıp %65±5 nem oranına ayarlanarak ısıya dayanıklı polipropilen torbalara 1 kg olacak şekilde doldurulmuştur. Sterilizasyon işlemi, 1 atm basınç altında, 121 °C'de 1.5 saat süreyle gerçekleştirilmiştir. Sıcaklığın 20-25 °C'ye düşmesi beklendikten sonra her bir torbaya yaklaşık %4 oranında P. eryngii miseli eklenerek misel aşılama işlemi gerçekleştirilmiştir.

Yetiştirme sürecinde, misel gelişimi için optimum sıcaklık olan 25 °C sağlanmıştır. P. eryngii mantar şapkaları 0.5, 1.0 ve 2.0 g chitosan/100 mL solüsyonlarına daldırılarak, 0°C sıcaklıkta ve %90-95 neme sahip soğuk hava depolarında muhafaza edilecektir.

Bu örneklerde hasat döneminde ve soğuk hava deposuna alındıktan sonra 4 gün aralıklarla renk (L*, b* C° ve h°) ve ambalaj içi gaz bileşenleri ve belirlenmiştir. Depolama sonunda kararmayı gözle görülmesini

EXAMPLE

sağlayan L değerinde azalışların olduğu ve ambalaj içi gaz bileşenlerinden de karbondioksit değerinde artışların olduğu belirlenmiştir.
Anahtar Kelimeler: Kitosan kaplama, Modifiye atmosfer paketleme, Renk değişimi, Ambalaj içi gaz kompozisyonu

EFFECTS OF CHİTOSAN COATİNGS ON COLOR AND GAS COMPOSİTİON OF KİNG OYSTER MUSHROOM (Pleurotus eryngii) UNDER MODİFİED ATMOSPHERE

ABSTRACT

In the present study, the effects of modified atmosphere conditions and the application of chitosan, an edible coating material, on the postharvest physiology of Pleurotus eryngii were investigated. The P. eryngii spawn was commercially procured from abroad through Sylvan Agricultural Products Industry and Trade Co. Ltd. (Kocaeli, Türkiye). Cultivation trials were conducted in environmentally controlled, rack-type growing rooms belonging to the Mushroom Research and Application Center of Van Yüzüncü Yıl University.
In the experiments, oak sawdust was used as the primary cultivation substrate, while gypsum and wheat bran were incorporated as supplements. The growing substrate was prepared to contain 90% oak sawdust, 9% wheat bran, and 1% gypsum. The mixture was homogenized and its moisture content was adjusted to 65 ± 5%, then filled into heat-resistant polypropylene bags at 1 kg per bag. Sterilization was carried out at 121 °C under 1 atm pressure for 1.5 hours. After allowing the substrate temperature to decrease to 20–25 °C, each bag was inoculated with approximately 4% P. eryngii spawn.
During the cultivation period, the optimum temperature for mycelial growth (25 °C) was maintained. Mushroom caps of P. eryngii were immersed in chitosan solutions at concentrations of 0.5, 1.0, and 2.0 g per 100 mL, and subsequently stored at 0 °C under 90–95% relative humidity in cold storage conditions.
Color parameters (L*, b*, C°, and h°) and in-package gas composition were determined at harvest and at 4-day intervals during storage. At the end of the storage period, a decrease in L* values, indicating visible browning, and an increase in carbon dioxide (CO2) levels within the package were observed.
Keywords: Chitosan coating, Modified atmosphere packaging, Color change, In-package gas composition

Van Yüzüncü Yıl Üniversitesi Bilimsel Araştırma Projeleri Koordinatörü (BAP) FYL-2025-11889 proje numarasıyla desteklenmiştir.

EXAMPLE

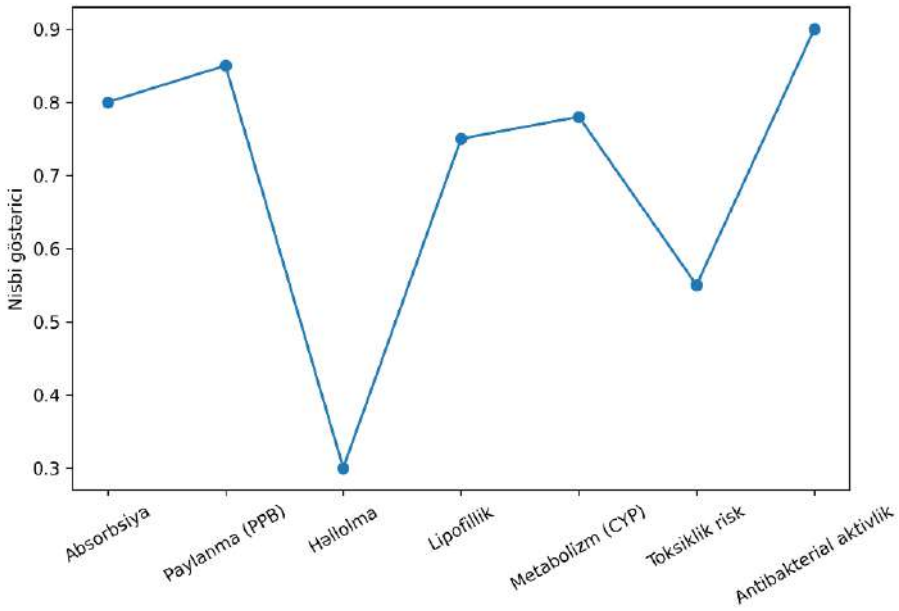
EFFECT OF LIPOPHILICITY AND STRUCTURE ON THE PHARMACOKINETIC BEHAVIOR OF DICHLORODIAZADIEN DERIVATIVE

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Abstract

The ADMET profile of (E)-1-(1-(4-(tert-butyl)phenyl)-2,2-dichlorovinyl)-2-(m-tolyl)diazene was investigated using the AdmetLab 3.0 software platform. The obtained results demonstrated that the compound possesses high lipophilicity (logP ~6.1). This characteristic facilitates its permeation through cellular membranes (Caco-2 ~−4.59); however, it may simultaneously limit its aqueous solubility. Distribution parameters indicated that the compound is characterized by high plasma protein binding (~94%) and a relatively large volume of distribution, suggesting an increased potential for tissue accumulation. From a metabolic perspective, (E)-1-(1-(4-(tert-butyl)phenyl)-2,2-dichlorovinyl)-2-(m-tolyl)diazene inhibits several CYP450 enzymes, which may contribute to metabolic stability while also increasing the risk of drug–drug interactions. Toxicological analysis revealed that the compound exhibits a moderate risk of hERG channel blockade; however, its overall toxicity profile was considered acceptable, as both the Ames mutagenicity test and carcinogenicity predictions were negative. SAR analysis demonstrated that the high lipophilicity associated with the m-tolyl group contributed to the most favorable docking binding energy (−7.0 kcal/mol). In conclusion, although (E)-1-(1-(4-(tert-butyl)phenyl)-2,2-dichlorovinyl)-2-(m-tolyl)diazene exhibits strong binding affinity, its elevated lipophilicity indicates that further pharmacokinetic optimization is required.

EXAMPLE



Keywords-Dihydrodiazadiene derivative, CYP450 enzymes, AdmetLab 3.0

EXAMPLE

MOLECULAR DOCKING AND STRUCTURE–ACTIVITY RELATIONSHIP STUDY OF (E)-1-(1-(4-(TERT-BUTYL)PHENYL)-2,2-DICHLOROVINYL)-2-(M-TOLYL)DIAZENE

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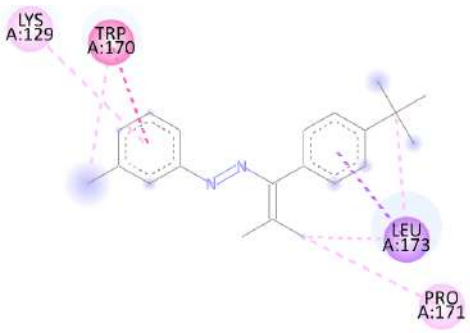
Abstract

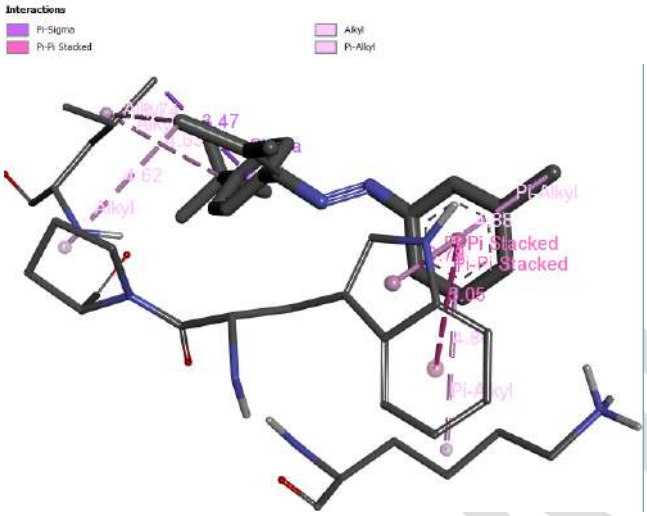
This study is devoted to the evaluation of the antibacterial potential and molecular docking properties of the compound (E)-1-(1-(4-(tert-butyl)phenyl)-2,2-dichlorovinyl)-2-(m-tolyl)diazene. The main objective of the research was to analyze the interaction of the compound with the DNA gyrase B enzyme and to determine its structure–activity relationship (SAR). In this work, molecular docking simulations were performed on DNA gyrase B derived from Escherichia coli, the validity of the obtained results was confirmed, and ligand–protein interactions were evaluated.

According to the molecular docking results, (E)-1-(1-(4-(tert-butyl)phenyl)-2,2-dichlorovinyl)-2-(m-tolyl)diazene exhibited the best performance among the investigated compounds, with a binding energy of −7.0 kcal/mol. This indicates that the compound forms the strongest interaction with the active site of the target protein. Interaction analysis revealed strong π–π stacking interactions with TRP A:170, as well as π–alkyl and π–sigma hydrophobic interactions with LEU A:173 and LYS A:129. These interactions significantly enhance the stability of the ligand–protein complex.

SAR analysis demonstrated that the m-tolyl substituent increases the lipophilicity of the molecule, resulting in stronger hydrophobic interactions within the binding pocket. Consequently, (E)-1-(1-(4-(tert-butyl)phenyl)-2,2-dichlorovinyl)-2-(m-tolyl)diazene exhibited the lowest binding energy and theoretically formed the most stable complex. It can therefore be concluded that the high docking performance of this compound confirms its potential as a potent antibacterial agent. In particular, the enhancement of hydrophobic and aromatic interactions may represent one of the key strategies in the design of new diazadiene derivatives.

EXAMPLE





Keywords- Dichlorodiazadienes, drug discovery, in silico methods, molecular docking

EXAMPLE

FULL TEXT



VERİYLE ÖRÜLEN ÇOCUKLUK: YAPAY ZEKA DESTEKLİPAZARLAMADA ÇOCUK TÜKETİCİNİN ALGORİTMİK NESNELEŞMESİ

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ÖZET

Dijital platformlarda geçirilen her dakika, çocukların davranışsal izlerini sistematik biçimde kayıt altına alan yapay zekâ altyapılarına veri sağlar. Kısa video izlemekten mobil oyun oynamaya, sesli asistanlarla etkileşime girmeye kadar uzanan gündelik dijital deneyimler, çocukları birer tüketici olmanın ötesinde, ticari değer taşıyan veri özneleri hâline getirmektedir. Bu çalışma, "verileştirilmiş çocuk tüketici" kavramını merkeze alarak yapay zekâ destekli pazarlama altyapılarının çocukların çevrimiçi davranışlarını nasıl gelire dönüştürülebilir veri akışlarına çevirdiğini kavramsal düzeyde ele almaktadır.

Bu çalışma üç temel soruyu yanıtlamayı amaçlamaktadır: Birincisi, yapay zekâ destekli pazarlama sistemleri çocukların davranış verilerini hangi mekanizmalar aracılığıyla yakalayıp işler? İkincisi, bu verileştirilmiş profillerden nasıl ticari değer elde edilmektedir? Üçüncüsü, bu sürecin çocukların özerkliği, mahremiyeti ve dijital iyi oluşu üzerindeki etik sonuçları nelerdir?

Çalışma, yapay zekâ destekli pazarlama, çocukların verileştirilmesi ve dijital iyi oluş literatürlerini tematik sentez yöntemiyle bir araya getiren kavramsal bir çerçeve sunmaktadır. Bu sentez, algoritmik profilleme, davranışsal hedefleme ve dikkat ekonomisi gibi kavramları çocuk gelişimi araştırmalarıyla bütünleştirerek literatürdeki önemli bir boşluğu doldurmaktadır. Bulgular, COPPA, GDPR-K ve UNICEF'in Çocuklar için Yapay Zekâ Kılavuzları gibi mevcut etik ve düzenleyici çerçevelerin, yapay zekâ sistemlerinin yarattığı derin ve kalıcı verileştirilmiş çocuk profilleriyle baş etmekte yetersiz kaldığını göstermektedir.

Bu çalışma, pazarlama stratejileri, mahremiyet politikaları ve çocuk refahı araştırmacılarına, yapay zeka destekli ticari sistemlerin çocukların kim olduğunu ve kim olacağını nasıl yeniden şekillendirdiğini analiz etmeleri için bütünleşik bir kavramsal dil sunmaktadır.

Anahtar Kelimeler: Verileştirilmiş çocuk tüketici, yapay zeka destekli pazarlama, algoritmik profilleme, dijital iyi oluş, çocuk mahremiyeti, dikkat ekonomisi

ALGORITHMICALLY OBJECTIFIED: THE DATAFIED CHILD CONSUMER IN AI-DRIVEN MARKETING ECOSYSTEMS

ABSTRACT

Every digital interaction a child has, whether watching a video, playing a mobile game, or engaging with a virtual assistant, generates behavioral traces systematically captured and monetized by AI-powered marketing infrastructures. This paper introduces and develops the concept of the "datafied child consumer" as a central analytical lens for examining how AI-driven marketing transforms children's online behaviors into predictive profiles and monetizable data streams.

The study addresses three conceptual questions: Through what mechanisms do AI-driven marketing systems capture and process children's behavioral data? How is commercial value extracted from datafied child profiles? And what are the ethical implications of this process for children's autonomy, privacy, and digital well-being?

Drawing on a thematic synthesis of literature across AI-driven marketing, childhood datafication, and digital well-being, this paper develops a high-level conceptual framework that maps the full cycle from data capture to monetization to ethical impact. The synthesis integrates algorithmic profiling, behavioral targeting, and attention economy research with child developmental psychology, identifying a critical gap in existing scholarship: the absence of a unified framework connecting AI-driven commercial strategies, datafication mechanisms, and child-centred ethics.

The analysis reveals that current ethical and regulatory frameworks, including COPPA, GDPR-K, and UNICEF's AI for Children guidelines, remain inadequate in addressing the depth and longitudinal persistence of AI-generated child profiles. The paper argues for a rights-based approach to AI-driven marketing that prioritizes transparency, developmental appropriateness, and genuine child-centred design over commercial data extraction.

This contribution offers marketing scholars, child-centred AI researchers, and policymakers a conceptual vocabulary for understanding how AI-driven commercial ecosystems are not merely targeting children as consumers, but actively reshaping who they are and who they will become.

Keywords: Datafication of childhood, AI-driven marketing, algorithmic profiling, digital well-being, children's privacy, attention economy

1.Giriş

Dijital ekosistemler, çocukluk deneyiminin ayrılmaz ve sürekli bir parçası hâline gelmiş; oyun, sosyalleşme ve öğrenme süreçleri giderek daha fazla yapay zekâ destekli platformlar üzerinden gerçekleşmeye başlamıştır (Mascheroni ve Siibak, 2021; Digital Child, 2021). Eğitim, eğlence ve sosyal medya hizmetleri, kullanıcı davranışlarını öngörmek, şekillendirmek ve ticarileştirmek üzere tasarlanmış algoritmik pazarlama sistemleriyle derinden iç içedir (Xie, 2025; Ruckenstein ve Granroth, 2020).

Çocuk kullanıcıların davranışsal izleri, tıklama geçmişi, izleme süresi, duraksama noktaları, oyun içi satın alma tercihleri, arama sorguları ve hatta yüz ve ses verileri gibi çok boyutlu sinyaller üzerinden ayrıntılı profillere dönüştürülmektedir (Livingstone, 2021; Human Rights Watch, 2022). Bu süreç, çocukları yalnızca reklam hedef segmentleri olarak değil, öngörülebilir ve yönetilebilir algoritmik varlıklar olarak nesneleştiren yeni bir çocukluk rejimi üretmektedir (Barassi, 2020; Zuboff, 2019).

Bu çalışmanın amacı, "verileştirilmiş çocuk tüketici" kavramını geliştirerek, yapay zekâ destekli pazarlama ekosistemlerinin çocukları nasıl veriye dönüştürdüğünü, bu veriden nasıl ticari değer ürettiğini ve bunun çocuk hakları, mahremiyet ve dijital iyi oluş açısından ne tür normatif gerilimler yarattığını bütüncül bir kavramsal çerçeveyle tartışmaktır (Alaimo ve Kallinikos, 2021; Pangrazio ve diğerleri, 2025). Çalışma, pazarlama, çocukluk çalışmaları, dijital sosyoloji ile etik ve regülasyon literatürleri arasında köprü kurmayı hedeflemektedir (Mascheroni ve Siibak, 2021; Livingstone, 2021).

2. Kavramsal Arka Plan

2.1. Çocuklukta verileşme

Verileşme (datafication) bireylerin gündelik eylemlerinin sistematik biçimde dijital izlere dönüştürülmesi ve bu izlerin ekonomik, yönetsel veya gözetim amaçlı işlenmesi süreci olarak tanımlanmaktadır (Alaimo ve Kallinikos, 2021; Zuboff, 2019). Çocukluk bağlamında verileşme, henüz gelişimsel olarak savunmasız olan bireylerin çevrimiçi ve çevrimdışı davranışlarının eğitim, oyun ve bakım uygulamaları aracılığıyla sürekli olarak toplanması ve uzun vadeli profil üretimine konu edilmesi anlamına gelir (Mascheroni ve Siibak, 2021; Jones ve Najera Mendoza, 2021).

Mascheroni ve Siibak (2021), çocukların hayatlarının eğitim teknolojileri, oyun platformları ve aile içi gözetim uygulamaları üzerinden her zamankinden daha yoğun biçimde veri üretir hale geldiğini ve bunun algoritmik sınıflandırma süreçleriyle yakından ilişkili olduğunu göstermektedir. Barassi (2020) ise çocukların daha doğmadan önce dahi veri izleri oluşturmaya başladığını ve bu izlerin "çocuk vatandaş" profillemesini mümkün kıldığını tartışmaktadır.

2.2. Yapay zeka destekli pazarlama ve algoritmik profilleme

Yapay zeka destekli pazarlama, tüketici verilerini büyük ölçekte ve gerçek zamanlı olarak işleyerek kişiselleştirilmiş içerik, fiyatlandırma ve teklif stratejileri üreten, veri güdümlü bir pazarlama pratiği setini ifade eder (Xie, 2025; Arslankara vd., 2022). Algoritmik pazarlama sistemleri; öneri motorları, öngörücü analitik modeller ve dinamik reklam açık artırmaları gibi araçlarla kullanıcıların gelecekteki davranışlarını tahmin ve teşvik etmeyi amaçlamaktadır (Ruckenstein ve Granroth, 2020).

Algoritmik profilleme, farklı veri kaynaklarından gelen sinyallerin bir araya getirilerek bireyler hakkında kestirimsel kategoriler ve skorlar üretilmesi sürecidir (Livingstone, 2021). Çocuklara ilişkin profiller, "yüksek katılım potansiyeli", "yüksek yaşam boyu değer" veya "savunmasız/kolay ikna edilebilir" gibi segmentler üretilmesine imkân tanıyarak, pazarlama mesajlarının yoğunluğunu ve biçimini belirlemede kullanılabilmektedir (Xie, 2025; Ruckenstein ve Granroth, 2020).

2.3. Dikkat Ekonomisi ve Çocuk kullanıcı

Dikkat ekonomisi yaklaşımı, dijital platformların temel çıktısının kullanıcı dikkati olduğunu; iş modellerinin ise bu dikkati reklamverenlere satmak üzerine kurulu bulunduğunu ileri sürer (Zuboff, 2019). Yapay zeka destekli algoritmalar, içerik akışlarını optimize ederek kullanıcıların platformda geçirdiği süreyi ve etkileşim sıklığını artırmak üzere tasarlanmaktadır (Daniel, 2025).

OECD'nin bulguları, çocuk ve gençlerin dijital ortamda giderek daha kırılgan hale geldiğini, yalnızca sınırlı bir kısmının yüksek düzeyde dijital iyi oluş bildirdiğini göstermektedir (OECD, 2025). Çocuklar, bilişsel kontrol ve reklam ile içeriği ayırt etme becerisi tam gelişmediği için dikkat ekonomisinin en kırılgan aktörleri arasında yer almakta; bu da algoritmik pazarlama stratejileriyle birleştiğinde manipülasyon riskini artırmaktadır (Stoilova vd., 2021; Zych ve Ortega-Ruiz, 2024).

3. Yöntem: Tematik Sentez Yaklaşımı

Bu çalışma, kavramsal bir inceleme olarak tasarlanmış ve yapay zeka destekli pazarlama, çocuklukta verileşme ve dijital iyi oluş literatürlerini tematik sentez yöntemi ile bir araya getirmiştir (Mascheroni ve Siibak, 2021; Pangrazio vd., 2025). Tematik sentez, farklı disiplin ve bağlamlarda üretilmiş çalışmalardan kavram ve temalar devşirerek, bunları üst-düzey bir kavramsal çerçevede yeniden düzenlemeyi amaçlayan nitel bir derleme stratejisidir (Alaimo ve Kallinikos, 2021).

Bu doğrultuda; (1) yapay zeka ve tüketici davranışı, algoritmik pazarlama ve kişiselleştirme, (2) çocukların dijital ortamlarla etkileşimi, çocuklukta veri toplama pratikleri ve çocuk mahremiyeti, (3) dijital iyi oluş, dikkat ekonomisi ve gençlerin ruh sağlığı üzerine son yıllara ait akademik çalışmalar ve politika dokümanları taranmış ve içerikleri tematik kodlama yoluyla analiz edilmiştir (Livingstone, 2021; Zych ve Ortega-Ruiz, 2024). Ayrıca COPPA, GDPR-K (çocuklara özgü GDPR hükümleri) ve UNICEF AI for Children yönergeleri gibi düzenleyici metinler de

normatif çerçevenin sınırlarını tartışmak için incelemeye dahil edilmiştir (European Union, 2016; FTC, 2013; UNICEF, 2021a).

4. Verileştirilmiş Çocuk Tüketici Kavramı

4.1. Kavramsal Tanım

"Verileştirilmiş çocuk tüketici", dijital izleri sürekli ve sistematik biçimde toplanan, bu veriler üzerinden algoritmik profillere dönüştürülen ve bu profiller üzerinden ticari değer üretilen çocuk kullanıcılara işaret eden bir kavram olarak önerilmektedir (Mascheroni ve Siibak, 2021; Barassi, 2020). Buradaki "verileştirilmiş", yalnızca yaş doğrulaması ya da kimlik teyidi gibi teknik süreçleri değil, çocuğun davranışsal ve psikografik örüntülerinin zaman içinde doğrulanması ve pekiştirilmesini de kapsar (Alaimo ve Kallinikos, 2021).

Bu kavram, çocukları verinin pasif nesneleri değil, algoritmik sistemlerin hedeflediği, eğittiği ve dönüştürdüğü öngörülebilir davranış paketleri olarak konumlandıran yeni bir pazar rasyonalitesini görünür kılar (Zuboff, 2019; Ruckenstein ve Granroth, 2020). Böylelikle çocuk, bir yandan hukuken korunması gereken bir hak öznesi, diğer yandan veri temelli iş modellerinin merkezinde yer alan bir ticari kaynak haline gelir (UNICEF, 2021b; OECD, 2025).

4.2. Verileştirme Döngüsü: Yakalama–Profil–Geri Bildirim

Verileştirilmiş çocuk tüketicinin oluşum süreci, veri yakalama, algoritmik profil üretimi ve davranışsal geri bildirim olmak üzere üç aşamalı bir döngü olarak kavramsallaştırılabilir (Xie, 2025). Platformlar önce çocukların izleme süresi, durakladığı anlar, oyun içi başarım ve satın alımlar, arama terimleri, coğrafi konum ve kullanılan cihazlar gibi çok çeşitli sinyalleri toplar (Livingstone, 2021; Human Rights Watch, 2022).

Bu sinyaller, makine öğrenmesi modelleri aracılığıyla ilgi alanları, satın alma eğilimi, dikkat süresi ve duygusal tepkisellik gibi kestirimsel özelliklere dönüştürülür (Ruckenstein ve Granroth, 2020). Ardından bu profiller doğrultusunda kişiselleştirilmiş içerik ve reklamlar gösterilir; bu hedefleme, çocuğun sonraki davranışlarını şekillendirerek profili daha da rafine eder ve veri döngüsünü kapatır (Alaimo ve Kallinikos, 2021; Mascheroni ve Siibak, 2021).

5. Yapay Zeka Destekli Pazarlama Mekanizmaları

5.1. Öneri Sistemleri ve Içerik Kürasyonu

Öneri sistemleri, çocuk kullanıcıların geçmiş izleme ve etkileşim geçmişine göre videolar, oyunlar veya uygulamalar önermek için yaygın biçimde kullanılmaktadır (Xie, 2025; Daniel, 2025). Bu sistemler, benzer kullanıcı kümelerinin tercihlerini kullanarak çocuklara yüksek etkileşim potansiyeline sahip içerikleri öne çıkarır ve böylece platformda geçirilen süreyi maksimize eder (Zuboff, 2019).

Eğitim ve sosyal medya alanındaki araştırmalar, bu tür algoritmik içerik kürasyonunun özellikle ergen ve çocukların zihinsel sağlık ve öznel iyi oluş üzerinde kaygı, depresyon ve benlik saygısı sorunları gibi riskleri artırabildiğini ortaya koymaktadır (Asian Journal of Psychiatry, 2025; Zych ve Ortega-Ruiz, 2024). Dijital iyi oluş ölçekleri de yoğun ve kontrolsüz dijital etkileşim ile daha düşük öznel iyi oluş ve yaşam memnuniyeti arasında ilişkiler olduğunu göstermektedir (Arslankara vd., 2022).

5.2. Davranışsal Hedefleme ve Programatik Reklamcılık

Programatik reklamcılık, gerçek zamanlı açık artırmalar yoluyla reklam envanterinin otomatik satın alınmasını ve kullanıcı profilleri temelinde kişiselleştirilmesini sağlar (Ruckenstein ve Granroth, 2020; Xie, 2025). Çocukların çevrimiçi davranışlarından türetilen ilgi alanları ve demografik kestirimler, reklamverenlerin yüksek dönüşüm potansiyeline sahip segmentlere odaklanmasına olanak tanımaktadır (Livingstone, 2021; IAPP, 2024).

Bu süreç, kişiselleştirilmiş reklam ile manipülatif ikna arasında ince bir çizgi yaratmakta; özellikle reklam ile içeriği ayırt etme becerisi tam gelişmemiş çocuklar için etik açıdan sorunlu bir alan oluşturmaktadır (Stoilova vd., 2021; OECD, 2025). COPPA ve benzeri düzenlemeler, çocuklara yönelik davranışsal hedefleme üzerinde kısıtlamalar getirse de, uygulama pratikleri ve yeni yapay zeka tabanlı modeller önemli gri alanlar yaratmaktadır (FTC, 2013; European Union, 2016).

5.3. Oyunlaştırma, Mikro Hedefleme ve Duygulanımsal Ölçüm

Oyunlaştırma unsurları (ödüller, puanlar, rozetler, süre kısıtlı kampanyalar) ve yapay zeka ile optimize edilen kullanıcı yolculukları, çocukların uygulama içi satın alma ve reklam izleme davranışlarını artırmak için yoğun biçimde kullanılmaktadır (Xie, 2025). Gelişen duygu tanıma, yüz ve ses analizi sistemleri, çocuğun duygusal tepkilerini gerçek zamanlı izleyerek içerik ve reklam akışını buna göre uyarlama potansiyeline sahiptir (IAPP, 2024).

Bu mekanizmalar, çocukların duygusal kırılganlıklarını ticari amaçlarla sömürü riskini artırırken, aynı zamanda rıza, bilgilendirme ve şeffaflık ilkelerini zayıflatmaktadır (UNICEF, 2021b; Ardent Privacy, 2024). Araştırmalar, bu tür yoğun etkileşim tasarımlarının çocukların dikkat süreleri, uyku düzeni ve öz düzenleme becerileri üzerinde olumsuz etkiler biriktirebileceğini göstermektedir (Daniel, 2025; Zych ve Ortega-Ruiz, 2024).

6. Ticari Değer Üretimi: Veri, Profil ve Pazar Mantığı

Yapay zeka destekli pazarlama sistemlerinde çocuklardan elde edilen veriler, sadece tekil reklam gösterimlerinin optimizasyonu için değil, uzun vadeli ticari stratejilerin şekillendirilmesi için de kullanılmaktadır (Xie, 2025; Zuboff, 2019). Çocukların yaşam boyu değerini tahmin etmeye yönelik modeller, erken yaşta marka bağlılığı ve ekosistem kilitlenmesi yaratmayı amaçlayan iş stratejileriyle ilişkilendirilmektedir (Ruckenstein ve Granroth, 2020; Mascheroni ve Siibak, 2021).

Buna ek olarak, çocuk profilleri üçüncü taraf veri aracılarının elinde, başka platform ve sektörlerde de kullanılabilecek ikincil veri ürünlerine dönüşebilmektedir (Jones ve Najera Mendoza, 2021; Human Rights Watch, 2022). Bu durum, veri paylaşımı zincirlerini opaklaştırmakta ve çocukların kişisel verileri üzerinde anlamlı bir kontrol sahibi olmasını küçük yaşlardan itibaren fiilen imkânsız hale getirmektedir (UNICEF, 2021b; Alaimo ve Kallinikos, 2021).

7. Etik Sonuçlar: Özerklik, Mahremiyet ve Dijital İyi Oluş

7.1. Çocuk Özerkliği ve Karar Verme

Algoritmik sistemler, çocukların neyi göreceğini, ne kadar süreyle etkileşimde bulunacağını ve hangi seçeneklerin görünür kılınacağını belirleyerek, karar verme alanlarını büyük ölçüde çerçeveler (Mascheroni ve Siibak, 2021; Daniel, 2025). Nitel çalışmalar, çocukların verileşme süreçlerini çoğunlukla parçalı ve sınırlı biçimde kavradığını; veri toplama pratiklerinin kapsamı ve sonuçlarına dair sistematik farkındalığın zayıf olduğunu göstermektedir (Stoilova vd., 2021).

Davranışları sürekli öngörülen ve yönlendirilen çocukların, uzun vadede teknolojiyle ilişkilerinde bağımlılık, dışsal motivasyona aşırı duyarlılık ve dikkat sürelerinde kısalma gibi sorunlar yaşaması olasıdır (Asian Journal of Psychiatry, 2025; Zych ve Ortega-Ruiz, 2024). Bu durum, çocukların gerçek tercih oluşturma ve eleştirel karar verme kapasitelerini zayıflatma riski taşımaktadır (OECD, 2025).

7.2. Mahremiyet, Veri Egemenliği ve Izlenebilirlik

Çocukların dijital mahremiyetini korumaya yönelik düzenlemeler çoğunlukla veri toplama için ebeveyn rızası, veri minimizasyonu ve belirli reklam pratiklerinin sınırlandırılması gibi ilkeler etrafında şekillenmiştir (European Union, 2016; FTC, 2013). Ancak yapay zeka destekli pazarlama sistemleri, çocuklar hakkında boylamsal ve çıkarımsal profiller üreterek gelecekteki davranışları da içeren geniş bir gizli veri alanı oluşturur (Barassi, 2020; Jones ve Najera Mendoza, 2021).

Bu tür çıkarımsal profillerin kapsamı, hangi aktörlerle paylaşıldığı ve ne kadar süre saklandığı çoğu zaman çocuğun ve ebeveynin bilgi alanı dışında kalmaktadır (UNICEF, 2021b; Human Rights Watch, 2022). Çalışmalar, ailelerin ve çocukların verilerinin hangi amaçlarla işlendiği konusunda genellikle belirsizlik yaşadığını ve algoritmik kararların sonuçlarını sorgulamak için gerekli araçlardan yoksun olduğunu ortaya koymaktadır (Stoilova vd., 2021; Mascheroni ve Siibak, 2021).

7.3. Dijital Iyi Oluş ve Ruh Sağlığı

Dijital iyi oluş literatürü, teknoloji kullanımının bilinçli yönetimi, ekran süresi dengesi, dikkat ve duygu düzenleme üzerindeki etkiler ve sosyal karşılaştırma süreçleri gibi boyutlara odaklanmaktadır (OECD, 2025; Arslankara vd., 2022). Ölçek geliştirme çalışmaları, yoğun dijital

medya kullanımının uyku kalitesi, benlik saygısı ve yaşam memnuniyetiyle olumsuz ilişkiler gösterebildiğini ortaya koymuştur (Arslankara vd., 2022).

Yapay zeka destekli sosyal medya ve içerik platformlarında, kişiselleştirilmiş akışların ergenlerin kaygı, depresyon ve beden memnuniyetsizliği ile ilişkili olabileceğine dair kanıtlar artmaktadır (Asian Journal of Psychiatry, 2025; Zych ve Ortega-Ruiz, 2024). OECD raporları da gençlerin dijital iyi oluşunun pek çok ülkede gerilemekte olduğunu, yalnızca küçük bir kısmının yüksek seviyede dijital iyilik hali bildirdiğini göstermektedir (OECD, 2025).

8. Düzenleyici Çerçevelerin Sınırları (COPPA, GDPR-K ve UNICEF AI for Children)

Çocukların çevrimiçi mahremiyetini korumaya yönelik COPPA, GDPR-K (çocuklara özgü GDPR hükümleri) ve UNICEF'in çocuklar için yapay zeka (AI for Children) yönergeleri, veri minimizasyonu, yaşa uygun tasarım ve ayrımcılık yasağı gibi kritik ilkeler getirmektedir (European Union, 2016; FTC, 2013; UNICEF, 2021a). UNICEF'in kılavuzu, çocuk haklarına dayalı yapay zeka tasarımı için şeffaflık, açıklanabilirlik ve katılım gibi ilkeleri öne çıkarır (UNICEF, 2021a; UNICEF, 2021b).

Bununla birlikte, bu çerçeveler daha çok veri toplama ve paylaşma süreçlerine odaklanmakta; yapay zeka sistemlerinin ürettiği boylamsal, çıkarımsal ve davranış şekillendirici profillerin derinliğini ve kalıcılığını kapsamlı biçimde ele almamaktadır (Barassi, 2020; Alaimo ve Kallinikos, 2021). Ayrıca küresel platform ekonomisinin karmaşık veri akışları ve tedarik zincirleri karşısında, bu düzenlemelerin fiili uygulanabilirliği ve denetimi de sınırlı kalmaktadır (Jones ve Najera Mendoza, 2021; Human Rights Watch, 2022).

9. Çocuk-Merkezli Bir Yaklaşım Önerisi

Bu çalışma, yapay zeka destekli pazarlama ekosistemlerinde çocukların konumunu yeniden düşünmek için hak-temelli ve çocuk-merkezli bir perspektif önermektedir (UNICEF, 2021a; OECD, 2025). UNICEF ve diğer kuruluşların çocuk odaklı yapay zeka kılavuzları, şeffaflık, sorumluluk ve çocuk katılımı gibi ilkelere vurgu yaparak bu yönde önemli bir başlangıç noktası sunmaktadır (UNICEF, 2021b; Ardent Privacy, 2024).

Bu çerçevede; şeffaf ve yaşa uygun bilgilendirme, gelişimsel açıdan uygun tasarım, veri minimizasyonu ve profil sınırlandırma, çocukların dijital yurttaşlık ve veri okuryazarlığı becerilerinin desteklenmesi gibi ilkelerin pazarlama teknolojilerinde bağlayıcı standartlara dönüştürülmesi gerektiği savunulmaktadır (Mascheroni ve Siibak, 2021; Zuboff, 2019). Böyle bir yaklaşım, çocukları yalnızca verinin nesnesi değil, aynı zamanda dijital ortamların şekillenmesinde hak sahibi özneler olarak konumlandırmayı mümkün kılacaktır (Digital Child, 2021; Pangrazio vd., 2025).

10. Sonuç

Yapay zeka destekli pazarlama ekosistemleri, çocukları pasif reklam alıcıları olmaktan çıkarıp, davranışsal verileri üzerinden şekillendirilen ve ticarileştirilen algoritmik özneler olarak yeniden tanımlamaktadır (Mascheroni ve Siibak, 2021; Xie, 2025). "Verileştirilmiş çocuk tüketici" kavramı, bu dönüşümün veri yakalama, profil üretimi ve davranışsal geri bildirim döngüleri üzerinden nasıl işlediğini görünür kılmakta; özerklik, mahremiyet ve dijital iyi oluş alanlarında ortaya çıkan etik gerilimleri sistematik biçimde analiz etmeye imkân vermektedir (Barassi, 2020; Alaimo ve Kallinikos, 2021).

Mevcut düzenleyici ve etik çerçeveler, yapay zeka kaynaklı çocuk profillerinin derinliği ve uzun vadeli etkileri karşısında önemli boşluklar barındırmakta; bu nedenle hak-temelli, çocuk-merkezli ve veri minimizasyonunu esas alan yeni bir politika ve tasarım paradigmasına ihtiyaç vardır (European Union, 2016; UNICEF, 2021a; OECD, 2025). Pazarlama araştırmacıları, çocuk-merkezli yapay zeka araştırmacıları ve politika yapıcılar için bu çalışma, çocuklukta verileşme sürecini anlamaya ve dönüştürmeye yönelik bütünlüklü bir kavramsal zemin sunmayı amaçlamaktadır (Pangrazio vd., 2025; Livingstone, 2021).

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EFFECT OF FOLIAR APPLICATION OF BORON AND ZINC ON COTTON QUALITY CHARACTERISTICS-II *

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Abstract

This study was carried out to determine the fiber technological characteristics of different Zinc (Zn) and Boron (B) applications in cotton. The study was carried out as the Randomized Complete Blocks Design with four replications under Siirt ecological conditions at 2022. In the study, MAY 455 cotton variety was used as materials. The study included 7 different (Control, Zn 45, Zn (45+60), Zn (45+60+75), B 45, B (45+60), B (45+60+75)) applications. According to the results of the study, no significant difference was found between the applications in terms of all the fiber quality characteristics (fiber length, fiber fineness, fiber strength, spinning consistency index, uniformity, elongation, short fiber index, moisture, brightness and yellowness) examined. These results show that zinc and boron application did not cause any difference in fiber quality. However, the results of this study do not coincide with the results obtained in previous studies, which indicated that zinc and boron caused significant differences in fiber quality characteristics. These results may be due to the environmental conditions in which the experiment was conducted and the materials used. However, continuing the study for at least one more year is important for making more definitive recommendations.

Keywords: Plant nutrient, boron, zinc, fiber quality properties, cotton

* This study is derived from Burhan URAZ's master's thesis.

YAPRAKTAN BOR VE ÇİNKO UYGULAMALARININ PAMUKTA KALİTE ÖZELLİKLERİNE ETKİSİ-II *

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Özet

Bu çalışma farklı Çinko ve Bor uygulama yöntemlerinin pamukta teknolojik özellikler üzerine olan etkisini belirlemek amacıyla yürütülmüştür. Çalışma 2022 yılında Siirt Üniversitesi Ziraat Fakültesi deneme alanında tesadüf blokları deneme desenine göre 4 tekrarlamalı olarak yürütülmüş ve denemede materyal olarak May 455 pamuk çeşidi ve yapraktan bor ve çinko mikro bitki besin elementleri kullanılmıştır. Denemede 7 farklı uygulama (Kontrol, Zn 45, Zn (45+60), Zn (45+60+75), Bor 45, Bor (45+60), Bor (45+60+75)) yer almıştır. Çalışmadan elde edilen sonuçlara göre lif uzunluğu, lif inceliği, lif kopma dayanıklılığı, iplik olabilirlik indeksi, üniformite, lif kopma uzaması, kısa lif indeksi, nem, parlaklık ve sarılık olmak üzere incelenen lif kalite özellikleri bakımından uygulamalar arasında önemli bir farklılık elde edilmemiştir, bu sonuçlar çinko ve bor uygulamasının lif kalitesinde herhangi bir farklılığa neden olmadığını ortaya koymuştur, ancak bu çalışmadan elde edilen sonuçlar önceki çalışmalarda elde edilen ve çinko ve bor'un lif kalite özelliklerinde önemli farklılıklar elde edildiğine ilişkin sonuçlar ile örtüşmemektedir. Bu sonuçlar denemenin yürütüldüğü çevre şartları ve kullanılan materyalden kaynaklanmış olabilir. Ancak çalışmanın en az bir yıl daha yürütülmesi daha net öneri yapılması bakımından önemlidir.

Anahtar Kelimeler: Bitki besin elementi, bor, çinko, lif kalite özellikleri, pamuk

* Bu çalışma Burhan URAZ'ın yüksek lisans tezinden türetilmiştir.

1. Giriş

Pamuk, tropikal ve subtropikal bölgelerde yaygın olarak yetiştirilen, hayati öneme sahip küresel bir lif bitkisidir. Tekstil endüstrisinde çok önemli bir rol oynar ve çok çeşitli ürünler için hammadde sağlar. Pamuğun önemi, ekonomik değerinin ötesine uzanır; zira dünya çapında milyonlarca çiftçinin geçim kaynağına da önemli ölçüde katkıda bulunur (Wahid ve ark., 2020; Abbas ve ark., 2022). Pamuk (*Gossypium hirsutum* L.), yüksek adaptasyon yeteneği, iyi lif kalitesi ve yüksek verimi nedeniyle dünya çapında en önemli lif bitkilerinden biridir. Beyaz altın olarak da bilinen pamuk, önemli bir gelir kaynağı ve tekstil endüstrisi için en önemli hammadde kaynağıdır. Pamuk verimi, dengesiz beslenme, hormonlar, çiçek ve koza dökülmesi gibi birçok nedenden etkilenmektedir. Verimlilikteki azalmanın nedenleri arasında özellikle mikro besin maddelerinin azalması, gübrelerin dengesiz uygulanması ve koza dökülmesi, koza kuruması, yaprak kızarması gibi fizyolojik bozuklukların ortaya çıkması yer almaktadır. Bunlar arasında makro ve mikro besin maddelerinin dengesiz kullanımı en büyük sorunlardan bir tanesidir (Hebbar ve ark., 2007).

Pamukta kalite oldukça önemlidir. Kaliteyi artırmanın birçok yolu vardır. Bu yollardan biri, besin maddelerinin yapraktan uygulanması gibi uygulanabilir yönetim uygulamalarını uyarlayarak ürün metabolizmasını hızlandırmaktır. Yapraktan gübreleme, anlık tepki, daha kolay uygulama, toprak gübrelemesinin desteklenmesi, besin eksikliklerinin düzeltilmesi, girdi maliyetinin azaltılması ve besin alımının iyileştirilmesi gibi birçok avantajla ürün büyümesini arttırmanın etkili yollarından biridir (Fageria ve ark., 2009). Pamuk diğer bitkilerde olduğu gibi üç temel makro bitki besin elementi olan azot, fosfor ve potasyuma gereksinim duyar. Yeryüzü toprakları bitki besin elementlerini barındırır ancak bu miktar optimum üretim için yeterli olmamaktadır. İlave olarak verilen gübreler, doğal olarak mevcut olan bitki besin elementleri ile ihtiyaç duyulanlar arasındaki farkı kapatır.

Pamuk üretiminde makro bitki besin elementlerinin yanı sıra bor, çinko, molibden gibi mikro besin elementlerine de gereksinim duyulur. Etkili bir gübreleme için toprak analizi yaptırmak önem arz etmektedir. Genel olarak bir dekarlık bir alandan 400 kg pamuk hasat edilerek topraktan uzaklaştırılır. Hasat edilen ürün, bitkinin büyümesi sırasında topraktan alınan besin maddelerini

içerir ve topraktaki besin maddeleri yerine konmadığı sürece sürdürülebilir bir üretim söz konusu olamaz. Yavaş ve kontrollü salınımlı gübreler, stabilize azotlu gübreler, sıvı gübrelerin yer altına enjeksiyonu ve yapraktan uygulanması gibi verimliliği artırılmış gübrelerin kullanımı giderek yaygınlaşmakta ve gübrelerin kullanım verimliliğini artırmaktadır (Jordan and Wakelyn 2010).

Bor (B), bitkiler tarafından düşük miktarlarda ihtiyaç duyulan temel bir besin maddesidir (Hussain ve ark., 2012). Bitki büyüme ve gelişmesinde birçok hayati rol oynar. Bitkilerin üretimindeki önemli sınırlamalardan biri, özellikle Boron (B) olmak üzere mikro besin maddelerinin yetersiz kullanımıdır; bu da pamuğun büyüme, verim ve kalite özelliklerine önemli bir risk oluşturmaktadır (Atique-ur-Rehman ve ark., 2022). Bitkilerin fizyolojik ve biyokimyasal süreçleri B eksikliğine karşı hassasiyet gösterirken, kabul edilebilir seviyelerin üzerindeki konsantrasyonlar toksik etkiler nedeniyle bitki büyüme ve gelişiminde azalmaya neden olur (Behera ve ark., 2023). Bor, çiçeklenmenin başlatılmasında ve tohum ve meyve üretiminde aktif rol oynar. Ayrıca, B uygulamasının, çoğunlukla kök ve çiçek gelişiminin seviyelerini düzenleyerek, bitkilerde P alımını ve entegrasyonunu artırdığı gösterilmiştir (Mehboob ve ark., 2022). Boron, polen oluşumunu kolaylaştırmada ve döllenme süreçlerini hızlandırmada çok önemli bir role sahiptir. Bu, bitkilerin üreme organlarındaki ideal hormon seviyelerinin düzenlenmesi yoluyla sağlanır ve sonuç olarak tohum gelişimi, büyüme ve lif kalitesi iyileşir (Rashidi ve Seilsepour, 2009). Ayrıca, optimal seviyenin üzerinde aşırı B kullanımı, bitkilerin sağlığı üzerinde zararlı etkilere sahiptir ve ürün nekrozuna ve kuru madde birikiminin azalmasına neden olur. B eksikliği fotosentezi ve yapraklardan meyvelere karbonhidrat taşınmasını engeller (Zhao ve Oosterhuis, 2002). Dahası, B eksikliği olgunlaşma süreci boyunca koza ve çiçeklerin dökülmesine neden olarak verimin azalmasına ve lif kalitesinin bozulmasına yol açar (Sankaranarayanan ve ark., 2010). Pamuğun gelişimi için vazgeçilmez olması ve bitki içinde hareket etme yeteneğinin sınırlı olması nedeniyle, B varlığı yaşam döngüsünün tamamı boyunca önemlidir (de Oliveira ve ark., 2006). B eksikliği, mevcut karbonhidrat miktarında azalmaya ve kozaların dökülmesine yol açar (Zhao ve Oosterhuis, 2003). Borun temel işlevi polen kısırlığını azaltmaktır; bu da çiçek sayısını artırır ve dolayısıyla ürün verimliliğini yükseltir. Çok sayıda çalışma, farklı ürünler için B dozlarını

optimize etmiştir. Bununla birlikte, yapraktan uygulanan borun pamukta koza tutunması ve lif kalitesi özellikleri üzerindeki etkisi nadiren araştırılmaktadır.

Çinko, mavimsi beyaz bir metal olup, yeryüzü kabuğunun yaklaşık %0,02'sini oluşturan 23. en büyük elementtir (Hussain ve ark., 2022). Temel bir element olan çinko, pamuğun farklı büyüme, metabolik ve üreme aşamalarında rol oynar (Anik ve ark., 2023). Pamuk bitkilerinde çeşitli metabolik süreçlerde yer alan 300'den fazla enzimin yapısal ve işlevsel bileşenidir (Wang ve ark., 2020). Çinko, tohum çimlenmesi (Li ve ark., 2004), su ilişkileri ve su kullanım verimliliği (Anik ve ark., 2023), ozmolit sentezi (Hatam ve ark., 2020), stomatal düzenleme (Sarwar ve ark., 2022), klorofil sentezi ve fotosentetik verimlilik (More ve ark., 2018), antioksidan savunma sistemi (Çakmak 2000), protein metabolizması (Sawan ve ark., 2001; Lacerda ve ark., 2018), membran stabilizasyonu (Ghanepour ve ark., 2015) ve üreme gelişimi (Sadeghzadeh, 2013) gibi süreçlerdeki rolü aracılığıyla bitki büyüme ve gelişimini etkilediği bilinmektedir. Düşük çinko kullanım verimliliği sorunu, alkali kireçli topraklarda çinkonun yapraktan uygulanmasıyla giderilebilir (Doolette ve ark., 2018). Bitkilerde çinko eksikliğinin belirtileri boğum aralarının kısalması, yaprak alanının azalması, bitki boyutunun küçülmesi, rozetlerin ortaya çıkması, sararma ve nekroz ile ortaya çıkar (Oliveira ve ark., 2023). Ahmed ve ark., (2020)'ye göre, yüksek çinko adsorpsiyon kapasitesine sahip topraklarda pamuk büyümesini ve verimini artırmak için yapraktan uygulama daha etkili olabilir. Çinko'nun yeterli düzeyde düzenlenmesi, pamuğun optimum büyümesi, verimi ve lif kalitesi için kritik öneme sahiptir (Çeçen ve Karademir, 2022).

2. Materyal ve Yöntem

Materyal

Çalışma Siirt Üniversitesi Ziraat Fakültesi Tarla Bitkileri Anabilim Dalı deneme alanında 2022 yılında kurulmuştur. Denemede May 455 pamuk çeşidi materyal olarak kullanılmıştır. Bor kaynağı olarak “Actıv Bor” ve çinko kaynağı olarak “Zincon” kullanılmıştır.

Deneme alanının toprak ve iklim özellikleri

Denemenin kurulduğu Siirt Üniversitesi Ziraat Fakültesi deneme alanı oldukça düşük eğime sahip, derin ve orta derin topraklardan meydana gelmiş olup, organik madde içerikleri düşüktür. Deneme alanı tuzluluk yönünden referans değerlerin oldukça altında olup tuzluluk problemi yoktur. Toprak katmanları boyunca ihtiva ettikleri yüksek nispetteki kil mineralleri sebebiyle kışları genişleyip şişmekte, yaz aylarında ise toprak yüzeyinden neredeyse 1 m derinliğinde çatlaklar oluşmaktadır.

Deneme sahasından ekim öncesi usulüne uygun bir şekilde toprak numuneleri alınarak bazı toprak özellikleri saptanmıştır. Saptanan özellikler Tablo 2.1'de verilmiştir.

Tablo 2.1. Deneme alanının toprak özellikleri

Tekstür	**Kil**	**Açıklama**
pH	7,98	Hafif alkali
EC (mS/cm)	0,363	Tuzsuz
Kireç (%$CaCO_3$)	13,02	Kireçli
Org.madde (%)	1,31	Düşük
N (%)	0,082	Düşük
P (ppm)	7,47	Az
K (me/100g)	0,98	Fazla
Fe (ppm)	5,70	Yeterli
Cu (ppm)	2,63	Yeterli
Zn (ppm)	0,23	Az
Mn (ppm)	6,04	Az

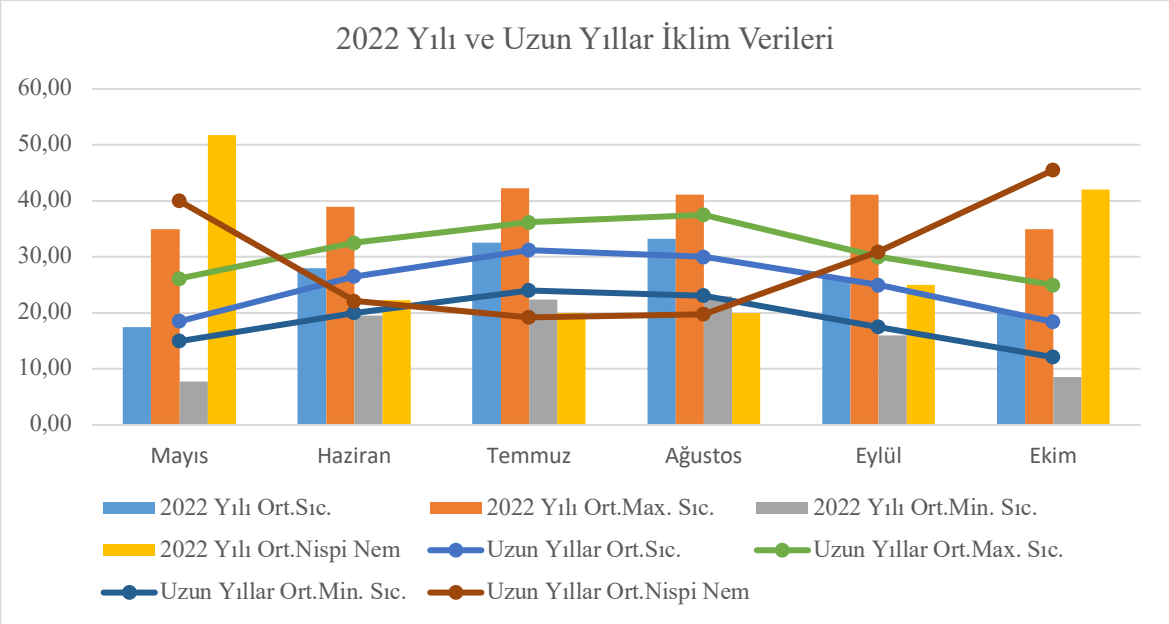
Kaynak: Siirt Üniversitesi Bilim ve Teknoloji Uygulama ve Araştırma Merkezi Laboratuvarı

Tablo 2.1. incelendiğinde, ekimden önce alınan toprak numunelerinde, bünyenin killi, pH hafif bazik, elektriksel iletkenlik referans değerlerin altında tuzsuz, kireç oranı yüksek, organik maddece fakir, azot içeriği bakımından düşük, fosfor, çinko ve mangan içeriği yönünden az,

demir içeriği ve bakır yönüyle yeterli, potasyum içeriği bakımından ise fazla olarak tespit edilmiştir.

Siirt ilinde yazlar sıcak ve kurak olup kışlar çok soğuk ve genelde parçalı bulutludur. Yıl içerisinde sıcaklık normalde -2°C ile 37°C arasında değişiklik göstermektedir. Kışları -8°C'nin altında düşebilirken, yazları 40°C'nin üzerinde sıcaklık yaşanabilmektedir (Url-1).Haziran ve Ekim ayları arasında genellikle yağış görülmemektedir. Gece ile gündüz arasındaki sıcaklık farkı yüksektir. Rüzgârlar geceleri doğu ve kuzeydoğudan, gündüzleri ise güney ve güneybatıdan esmekte iken kışın ise genellikle kuzey ve kuzeybatıdan esmektedir. Denemenin yürütüldüğü 2022 yılına ve uzun yıllara ait sıcaklık değerleri Tablo 2.2'de verilmiştir.

Tablo 2.2. Denemenin yürütüldüğü 2022 yılı ile uzun yıllar iklim verileri



* Meteoroloji Genel Müdürlüğü, Uzun Yıllar Ortalaması: 1950-2015

Tablo 2.2 incelendiğinde denemenin yürütüldüğü 2022 yılı ortalama sıcaklık değerlerinin Mayıs ayı hariç diğer aylarda uzun yıllar ortalamasının üzerinde olduğu, ortalama maksimum sıcaklığın tüm aylarda uzun yıllar sıcaklıklarından daha yüksek olduğu Eylül ve Ekim aylarında bu farkın 10 °C' ye kadar ulaştığı, ortalama minimum sıcaklıkların Ekim ayı dışında genel olarak

paralel olduğu ancak Ekim ayında bu değerin uzun yıllar ortalamasının 3,5 ºC altında kaldığı nispi nemin ise uzun yıllar ile paralel seyrettiği izlenebilmektedir.

Toprak hazırlığı ve ekim

Denemenin kurulduğu tarla alanı sonbaharda pullukla derin bir şekilde sürülmüş ilkbaharda ekimden önce kültivatör ile yüzlek bir şekilde işlenmiş ve ekim yapılmadan önce 3 defa tapan çekilerek deneme alanı pamuk ekimi için uygun bir duruma getirilmiştir. Deneme alanı ekime hazır hale getirildikten sonra parselasyon yapılmıştır. Çalışmada ekim işlemleri mini ekim makinesi ile yapılmıştır, ekimde her parselin boyu 6 m ve 4 sıradan oluşturulmuştur. Her bir parselin genişliği 4 x 0,7 m = 2.8 m olup, bloklar arasında 2 m aralık bırakılmıştır. Buna göre araştırmanın eni 28 m, uzunluğu ise 30 m olmak üzere, toplam alan 19,6 m x 30 m = 588 m2 olmuştur.

Sıra arası uzaklık ekimde 0,70 m sabit tutulmuş, sıra üzeri uzaklık ise seyreltme yapılarak 10-15 cm olacak şekilde ayarlanmıştır. Ekimde her bir parsel alanı 6 m x 4 sıra x 0,70 m: 16,8 m2 olmuştur. Deneme alanından ekim öncesinde toprak örnekleri alınarak merkezi laboratuvarda toprak analizleri yapılmış ve bitkinin gereksinim duyduğu gübre miktarı belirlenmiştir. Ekim esnasında bitki için gerekli olan azotun yarısı (hızlı hareket ettiği için) ile fosforun tamamı (geç yarayışlı hale geldiği için) uygulanmış, geriye kalan azotun ikinci yarısı ise taraklanma döneminde ilk sulamadan önce ara çapa yapıldığı esnada kombine gübre makinesi ile verilmiştir.

Siirt Üniversitesi Ziraat Fakültesi deneme alanlarında 2022 yılı pamuk yetiştirme döneminde tesadüf blokları deneme deseninde göre 4 tekerrürlü olarak kurulan araştırmada kontrol dâhil 7 farklı uygulama yapılmıştır. Uygulamalara ilişkin ayrıntılar aşağıda belirtilmiştir. Kontrol uygulamasında bölgede üreticiler tarafından uygulanan standart gübreleme (16 kg/da azot + 8 kg/da fosfor) uygulanmıştır. Diğer uygulamalar ise kontrole ek olarak yapraktan şarjlı sırt pülverizatörü ile püskürtülmek suretiyle uygulanmıştır.

Uygulamalar

1. Kontrol Geleneksel gübreleme; 16 kg/da N, 8 kg/da P_2O_5
2. Zn (45) Ekimden 45 gün sonra Zn uygulaması
3. Zn (45 + 60) Ekimden 45 ve 60. gün sonra olmak üzere 2 kez uygulama
4. Zn (45 + 60 + 75) Ekimden 45, 60 ve 75. gün sonra olmak üzere 3 kez uygulama
5. B (45) Ekimden 45 gün sonra B uygulaması
6. B (45 + 60) Ekimden 45 ve 60. gün sonra olmak üzere 2 kez uygulama
7. B (45 + 60 + 75) Ekimden 45, 60 ve 75. gün sonra olmak üzere 3 kez uygulama

Bakım işlemleri

Bitkiler 15 cm boya eriştiklerinde sıra üzeri uzaklık 10-15 cm olacak şekilde seyreltilmiş, deneme boyunca 3 kere el çapası, 2 kere makina çapası geçmiştir. Bitki gelişim periyodu süresince yabancı ot ve zararlı kontrolleri fakültemiz bitki koruma bölümü ile işbirliği halinde yapılmıştır. Denemenin alanına bölgede bazı yıllar epidemi yapan "Dikenli kurt" ve bölgede hemen hemen her pamuk üretim sezonunda görülmekte olan "Yeşil kurt"a karşı olmak üzere feromon tuzaklar konulmuştur. Bitki koruma bölümü uzman hocalarının önerileri doğrultusunda denemin yürütüldüğü pamuk üretim sezonunda zararlı popülasyonu eşik değeri geçmediği için ilaçlama yapmaya gerek duyulmadığı için ilaçlı mücadele yapılmamıştır. Denemede her parsele etiket takılarak gözlem ve uygulamaların hassas yapılması sağlanmıştır . Denemede basınçlı sulama sistemlerinden en verimli sulama yöntemi olan damla sulama sistemi kullanılmıştır. Sulamalarda bitkinin su tüketimi dikkate alınarak sulama programı planlanmıştır. Sulamaya taraklanma döneminde başlanmış ve kozaların % 10'u açtığında sonlandırılmıştır. Deneme süresince incelenen özellikler alt başlıklar halinde aşağıda açıklanmıştır.

Lif teknolojik analizlerinin belirlenmesi

Lif kalite analizleri GAP Uluslararası Tarımsal Araştırma ve Eğitim Merkezi Müdürlüğü Lif kalite analiz laboratuvarında HVI (High Volume Instrument) cihazı ile belirlenmiştir. İncelenen lif kalite özelliklerine ait ayrıntılar aşağıda belirtilmiştir.

Lif uzunluğu (mm)

Lif inceliği (micronaire)

Lif kopma dayanıklılığı (g/tex)

İplik olabilirlik indeksi (SCI)

Lif üniformite oranı (%)

Lif kopma uzaması (%)

Kısa lif oranı (%)

Lif olgunluk indeksi (%)

Nem (%)

Parlaklık (Rd)

Sarılık (+b)

Hasat

Deneme hasadında ekilen 4 sıranın sağdan ve soldan birer sıraları kenar tesiri olarak bırakılmış, ortadaki iki sıradan her sıranın başından ve sonundan 0,5 m ölçülerek hasat edilmemiş geri kalan alan hasat edilmiştir. Hasat elle 17.10.2022 tarihinde yapılmıştır.

İstatistiki analizler

Denemeden elde edilen tüm veriler, kullanılan deneme desenine uygun olarak JUMP istatistik paket program kullanılarak analiz edilmiştir. Gruplamalar $LSD_{(0.05)}$'e göre yapılmıştır.

3. Bulgular ve Tartışma

Araştırmada incelenen özelliklerden lif uzunluğu, lif inceliği, lif kopma dayanıklılığı, iplik olabilirlik indeksi, lif üniformite oranı ve Lif Kopma Uzaması özelliklerine ilişkin ortalama değerler ve oluşan gruplamalar Çizelge 3.1' de verilmiştir.

Çizelge 3.1 İncelenen özelliklere ait ortalama değerler ve oluşan gruplamalar

Uygulama	Lif Uzunluğu (mm)	Lif İnceliği (micron air)	Lif Kopma Dayanıklılığı (g tex^{-1})	SCI	Lif Üniformite Oranı (%)	Lif Kopma Uzaması (%)
1. Kontrol	29,41	5,08	35,30	145,50	83,62	5,65
2. Zn (45)	28,93	5,47	34,05	142,25	84,60	5,82
3. Zn (45 + 60)	29,15	5,23	34,50	142,50	83,97	5,65
4. Zn (45 + 60 +75)	29,21	5,30	35,77	149,50	84,50	5,67
5. Bor (45)	28,96	5,29	32,75	136,50	83,80	5,60
6. Bor (45 + 60)	28,70	5,50	33,05	133,25	83,55	5,57
7. Bor (45 + 60 +75)	29,00	5,17	34,72	143,00	84,02	5,45
Ortalama	29,05	5,29	34,30	141,78	84,01	5,63
CV (%)	2,26	4,83	5,32	6,11	1,01	3,52
LSD (0.05)	ÖD	ÖD	ÖD	ÖD	ÖD	ÖD

*** ; % 1 seviyesinde, * ; % 5 seviyesinde önemlidir.*

Lif uzunluğu (mm) : Çizelge 3.1'de lif uzunluğu bakımından değerler incelendiğinde lif uzunluğuna ait ortalama değerlerin, 27,89 mm ile 29,41 mm arasında değişim gösterdiği; uygulamalar arasında önemli istatistiksel farklılıkların bulunmadığı ve araştırmanın genel ortalamasının 29,05 mm olduğu görülmektedir. En düşük lif uzunluğunun 28,70 mm ile 7 numaralı uygulamadan elde edildiği, en yüksek lif uzunluğunun ise 29,41 mm ile 1 no'lu uygulamadan sağlandığı görülmektedir. Bu uygulamayı 4 no'lu uygulama 29,21 mm lif uzunluğu değeri ile takip

etmiştir. Lif uzunluğu bakımından tüm uygulamaların sonuçları göz önünde bulundurulduğunda çinko ve bor uygulamasının yapılmadığı kontrol uygulanması en yüksek lif uzunluğu değerini göstermiş bu uygulamayı Çinko'nun ekimden 45, 60 ve 75 gün sonra yapıldığı uygulama izlemiştir. Bu çalışmanın sonucu önceki çalışmalardan Emara (2016), Buriro ve ark.(2016), Rajput ve ark. (2016), Tekin (2011), Sankaranarayanan ve ark. (2010), Abid ve ark. (2007), Durmaz (2002), Rezaei ve Malakouti (2001)'nin elde ettiği bulgular ile uyum göstermektedir, ancak çalışmalarında yapılan uygulamalar arasında önemli farklılıklar elde etmiş olan Shah ve ark. (2017) ile Yıldırım (2003)'ün elde etmiş oldukları sonuçlar ile örtüşmemektedir.

Lif inceliği (micronaire) : Lif inceliği bakımından değerler incelendiğinde lif inceliğine ait ortalama değerlerin 5,08 ile 5,50 micronaire arasında değişim gösterdiği; uygulamalar arasında önemli istatistiksel farklılıkların bulunmadığı ve araştırmanın genel ortalamasının 5,29 micronaire olduğu görülmektedir. En düşük değerin 5,08 micronaire ile 1 no'lu uygulamadan elde edildiği, en yüksek lif inceliği değerinin ise 5,50 micronaire ile 6 no'lu uygulamadan sağlandığı görülmektedir (Çizelge 3.1). Bu çalışmanın sonucu önceki çalışmalardan Emara (2016), Buriro ve ark.(2016), Rajput ve ark. (2016), Tekin (2011), Sankaranarayanan ve ark. (2010), Abid ve ark. (2007), Durmaz (2002), Rezaei ve Malakouti (2001)'nin elde ettiği bulgular ile uyum göstermektedir, ancak çalışmalarında yapılan uygulamalar arasında önemli farklılıklar elde etmiş olan Shah ve ark. (2017) ile Yıldırım (2003)'ün elde etmiş oldukları sonuçlar ile örtüşmemektedir.

Lif kopma dayanıklılığı (g tex^{-1}) : Lif kopma dayanıklılığı bakımından değerler incelendiğinde lif kopma dayanıklılığına ait ortalama değerlerin 32,75 ile 35,77 g/tex arasında değişim gösterdiği; uygulamalar arasında önemli istatistiksel farklılıkların bulunmadığı ve araştırmanın genel ortalamasının 34,30 g/tex olduğu görülmektedir. En düşük değerin 32,75 g/tex ile 7 no'lu uygulamadan, en yüksek değerin ise 35,77 g/tex ile 4 numaralı uygulamadan sağlandığı görülmektedir (Çizelge 3.1). Bu çalışmanın sonucu önceki çalışmalardan Sankaranarayanan ve ark., (2010) ile Emara (2016)'nın elde ettiği sonuçlar ile örtüşmektedir, ancak çalışmalarında yapılan uygulamaların lif kopma dayanıklılığında önemli farklılıklara yol açtığını bildiren Rajput ve ark. (2016), Tekin (2011) ile Durmaz (2002)'nıin sonuçları ile örtüşmemektedir.

İplik olabilirlik indeksi : İplik olabilirlik indeksi yönünden elde edilen verilerin uygulamalar arasında değişmek üzere 133,25 ile 149,50 arasında değişim gösterdiği, ve uygulamalar arasında istatistiksel önem seviyesinde bir farklılığın oluşmadığı izlenebilmektedir. En düşük değer 133,25 ile 6 no'lu uygulamadan elde edilmiş, en yüksek değer ise 149,50 ile 4 no'lu uygulamadan sağlanmıştır.

Lif üniformite oranı değeri (%): Çizelge 3.1'den üniformite oranı yönünden değerlerin uygulamalar arasında değişmek üzere %83,55 ile 84,60 arasında değişim gösterdiği, ancak uygulamalar arasında istatistiksel önem seviyesinde bir farklılığın oluşmadığı görülmektedir. En düşük değer %83,55 ile 6 numaralı uygulamadan elde edilmiştir. En yüksek değer ise %84,60 ile 2 numaralı uygulamadan sağlanmıştır. Bu çalışmanın sonucu önceki çalışmalardan Sankaranarayanan ve ark. (2010), Tekin (2011) ile Emara (2016)'nın bildirdikleri sonuçlar ile uyum içinde olmamaktadır.

Lif kopma uzaması (%): Çizelge 3.1'den lif kopma uzaması yönüyle değerlerin uygulamalar arasında değişmek üzere %5,45 ile %5,82 arasında değişim gösterdiği, ancak uygulamalar arasında istatistiksel önem düzeyinde bir farklılığın olmadığı izlenebilmektedir. En düşük değer %5,45 ile 7 numaralı uygulamadan elde edilmiştir. En yüksek değer ise %5,82 ile 2 numaralı uygulamadan elde edilmiştir.Uygulamaların genel ortalamasının %5,63 olduğu görülmektedir. Bu çalışmanın sonucu önceki çalışmalardan Sankaranarayanan ve ark., (2010)'nın ortaya koyduğu sonuçlar ile benzerlikler göstermektedir.

Araştırmada incelenen özelliklerden kısa lif oranı, olgunluk, nem, parlaklık ve sarılık özelliklerine ilişkin ortalama değerler ve oluşan gruplamalar Çizelge 3.2' de verilmiştir.

Çizelge 3.2 İncelenen özelliklere ait ortalama değerler ve oluşan gruplamalar

Uygulama	Kısa Lif Oranı (Adet)	Olgunluk (g)	Nem (g)	Parlaklık (Adet)	Sarılık (Adet)
1. Kontrol	7,35	0,89	7,52	74,37	10,20
2. Zn (45)	7,57	0,90	7,45	74,65	10,00
3. Zn (45 + 60)	7,47	0,89	7,45	73,67	10,20
4. Zn (45 + 60 +75)	7,87	0,89	7,57	75,17	10,20
5. Bor (45)	7,05	0,89	7,37	74,47	10,12
6. Bor (45 + 60)	7,65	0,90	7,35	74,60	10,02
7. Bor (45 + 60 +75)	7,62	0,90	7,47	72,50	10,02
Ortalama	7,51	0,89	7,45	74,20	10,11
CV (%)	17,75	0,77	3,81	1,82	3,19
LSD (0.05)	ÖD	ÖD	ÖD	ÖD	ÖD

*** ; % 1 seviyesinde, * ; % 5 seviyesinde önemlidir.*

Kısa lif oranı SFI (%): Çizelge 3.2'den kısa lif indeksi yönüyle değerlerin uygulamalara göre değişmek üzere %7,05 ile %7,87 arasında değişim gösterdiği izlenebilmektedir. Uygulamalar arasında istatistiksel önem düzeyinde bir farklılığın olmadığı izlenebilmektedir. En düşük değer %7,05 ile 5 numaralı uygulamadan elde edilmiştir. En yüksek değer ise % 7,87 ile 4 numaralı uygulamadan elde edilmiştir. Denemenin genel ortalamasının % 7,51 olduğu görülmektedir. Bu çalışmanın sonucu önceki çalışmalardan Tekin (2011)'in elde ettiği sonuçlar ile benzerlik göstermektedir.

Lif olgunluk indeksi : Çizelge 3.2'den Olgunluk değerleri yönüyle elde edilen bulgular uygulamalara göre değişmek üzere % 89 ile %90 arasında değişim göstermiştir, ancak uygulamalar arasında istatistiksel önem seviyesinde bir değişikliğin olmadığı gözlenmiştir.

Nem (%) : Çizelge 3.2'den Nem değerleri yönüyle elde edilen sonuçlar uygulamalara göre değişmek üzere % 7,35 ile 7,57 arasında değişim göstermiştir, ancak uygulamalar arasında önemli bir farklılık elde edilmemiştir. Denemenin genel ortalamasının %7,45 olduğu görülmektedir.

Parlaklık (Rd) : Çizelge 3.2'den Parlaklık değerleri yönüyle elde edilen sonuçların uygulamalara göre değişmek üzere 72,50 ile 75,17 arasında değişim gösterdiği, ancak uygulamalar

arasında istatistiksel olarak bir faklılığın oluşmadığı belirlenmiştir. Araştırmanın genel ortalamasının 74,20 olduğu izlenebilmektedir.

Sarılık (+b) : Çizelge 3.2'den Sarılık değerleri yönünden elde edilen sonuçlar uygulamalara göre değişmek üzere % 10,00 ile 10,20 arasında değişim göstermiştir, yapılan istatistiksel analiz sonuçları yapılan uygulamaların bu özellik üzerine etkili olmadığını göstermiştir.

4. Sonuç

Yürütülen bu çalışmada ekimden 45 (taraklanma dönemi), 60 (çiçeklenme dönemi) ve 75 (çiçeklenme doruğu) gün sonra yapraktan çinko ve bor bitki besin elementleri uygulanmıştır. Taraklanma, çiçeklenme ve çiçeklenme doruğunda gerçekleştirilen çinko uygulamasının incelenen lif kalite özellikleri üzerine bir etkisinin olmadığı ortaya konulmuştur. Literatür araştırmalarında pamukta çinko uygulamasının hem önemli etsinin olduğuna hem de önemsiz olduğuna ilişkin sonuçlar bulunmaktadır. Bu nedenle çalışmanın en az bir yıl daha yürütülerek bu konuda bir öneride bulunmak daha sağlıklı olabilir.

Bor uygulamalarının sonuçları değerlendirildiğinde, ekimden sonra 45, 60 ve 75'inci günlerde yapılan lif kalite özellikleri üzerine bir etkisinin olmadığı ortaya konulmuştur. Önceki çalışmalarda pamukta bor uygulamasının hem önemli etsinin olduğuna hem de önemsiz olduğuna ilişkin sonuçlar bulunmaktadır. Bu nedenle çalışmanın en az bir yıl daha yürütülerek bu konuda bir öneride bulunmak daha sağlıklı olabilir.

İncelenen tüm lif kalite özellikleri bakımından uygulamalar arasında önemli bir farklılık elde edilmemiştir, bu sonuçlar çinko ve bor uygulamasının lif kalitesinde herhangi bir farklılığa neden olmadığını ortaya koymuştur, ancak bu çalışmadan elde edilen sonuçlar önceki çalışmalarda elde edilen ve çinko ve bor'un lif kalite özelliklerinde önemli farklılıklar elde edildiğine ilişkin sonuçlar ile örtüşmemektedir. Bu sonuçlar denemenin yürütüldüğü çevre şartları ve kullanılan materyalden kaynaklanmış olabilir. Ancak çalışmanın en az bir yıl daha yürütülmesi daha net öneri yapılması bakımından önemlidir.

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SEÇİMİ YÖNLENDİREN ALGORİTMALAR: YAPAY ZEKÂ DESTEKLİ PAZARLAMADA ÇOCUK TÜKETİCİNİN DAVRANIŞSAL GÜVENLİK AÇIKLARI ÜZERİNE KAVRAMSAL BİR İNCELEME

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ÖZET

Yapay zeka destekli pazarlama platformları, çocukların dijital deneyimlerini yeniden biçimlendirirken yalnızca reklam göstermekle kalmamakta; dikkat, tercih ve karar alma süreçlerini etkileyen algoritmik ortamlar inşa etmektedir. Kişiselleştirilmiş içerik akışları, otomatik davranışsal müdahaleler ve dinamik öneri sistemleri aracılığıyla gerçekleşen bu süreç, davranışsal ekonomi literatüründe "seçim mimarisi" olarak tanımlanan yapıyı çocuk tüketici ortamlarına taşımaktadır. Çocuklara yönelik dijital reklam pazarının hızla büyümesi ve çocukların günlük ekran sürelerinin belirgin biçimde artması, bu alandaki ticari ölçeği ve maruz kalma yoğunluğunu açıkça ortaya koymaktadır.

Bu çalışma, algoritmik yönlendirmenin çocuk tüketici ortamlarındaki mekanizmalarını kavramsal düzeyde analiz etmektedir. Çalışma şu üç temel soruyu yanıtlamayı amaçlamaktadır: Algoritmik yönlendirme, çocukların bulunduğu dijital ortamlarda nasıl bir seçim mimarisi olarak işlev görmektedir? Çocukluk ve ergenlik döneminin hangi psikolojik ve gelişimsel özellikleri bu yönlendirmelere karşı duyarlılığı artırmaktadır? Ve bu sürecin çocuk tüketicilerin özerkliği ve dijital iyi oluşu üzerindeki etik sınırları nerede çizilmelidir?

Çalışma, davranışsal ekonomi, gelişimsel psikoloji ve yapay zeka pazarlama etiği literatürünü tematik sentez yöntemiyle bütünleştiren özgün bir kavramsal çerçeve geliştirmektedir. Bu çerçeve, çift sistem kuramına dayalı olarak algoritmik yönlendirmenin öncelikle otomatik ve sezgisel karar süreçlerini hedef aldığını öne sürmektedir. Yönetici işlevleri henüz olgunlaşmamış, sosyal ve duygusal uyaranlara karşı duyarlılığı yüksek ve ikna niyetine yönelik eleştirel değerlendirme kapasitesi sınırlı çocuk tüketicilerin bu yönlendirmelere karşı orantısız biçimde savunmasız olduğu argümanlaştırılmaktadır.

Bu çalışma, yapay zeka sistemlerinde şeffaflık ve hesap verebilirlik ilkelerinin çocuklara yönelik ticari ortamlarda nasıl uygulanabilir hale getirilebileceğini tartışarak politika yapıcılar, araştırmacılar ve sektör paydaşları için bütünleşik bir kavramsal temel sunmaktadır.

Anahtar Kelimeler: Algoritmik yönlendirme, seçim mimarisi, çocuk tüketici, yapay zeka pazarlaması, davranışsal etki, dijital iyi oluş, şeffaflık

ENGINEERED CHOICES: ALGORITHMIC NUDGING, BEHAVIORAL VULNERABILITY, AND THE CHILD CONSUMER IN AI-DRIVEN MARKETING ENVIRONMENTS

ABSTRACT

AI-driven marketing platforms no longer simply display advertisements; they engineer digital environments that systematically guide children's attention, preferences, and decisions. Through personalized content feeds, automated behavioral interventions, and dynamic recommendation systems, algorithmic nudging has emerged as a powerful form of choice architecture operating within the ecosystems child consumers inhabit daily. The rapid expansion of the kids' digital advertising market and the sustained growth of children's daily screen time underscore both the commercial scale of this phenomenon and the intensity of child consumers' exposure to algorithmically structured environments.

This paper develops a conceptual framework for understanding how algorithmic nudging functions as a distinct form of choice architecture within child consumer environments, and what implications this carries for children's autonomy and digital well-being. Three guiding questions structure the analysis: How does algorithmic nudging operate as a form of choice architecture in the digital environments frequented by child consumers? Which psychological and developmental characteristics of childhood amplify susceptibility to AI-driven nudges? And where should the ethical boundaries between beneficial guidance and manipulative persuasion be drawn in contexts involving child consumers?

Synthesizing literature across behavioral economics, developmental psychology, and AI marketing ethics, the paper constructs a three-layer conceptual model. The first layer, grounded in dual-system theory, establishes that algorithmic nudges are disproportionately effective because they dynamically engage automatic processing while bypassing deliberative reasoning. The second layer integrates a developmental lens, arguing that child consumers' immature executive functions, heightened sensitivity to social and emotional cues, and underdeveloped skepticism toward persuasive intent render them uniquely vulnerable to embedded digital nudges. The third layer situates these dynamics within the commercial imperatives of the expanding kids' digital advertising market, critically examining how AI personalization and predictive targeting intensify traditional marketing pressures on child consumers.

The framework offers researchers, policymakers, and industry practitioners a structured conceptual language for identifying where transparency, explainability, and child-centred design principles must be operationalized to protect the digital well-being of young consumers.

Keywords: Algorithmic nudging, choice architecture, child consumer, AI-driven marketing, behavioral influence, digital well-being, transparency

1. Giriş

Dijital pazarlama ekosistemleri, çocukların çevrimiçi ortamlarda gerçekleştirdiği her etkileşimi kişiselleştirilmiş içerik akışları ve hedefli reklamlarla çevrelenen bir seçim ortamına dönüştürmektedir (Amerikan Pediatri Akademisi [AAP], 2020; Çocuklar ve Ekranlar Vakfı, 2024). Yapay zeka destekli öneri sistemleri, puanlama algoritmaları ve mikro hedefleme altyapıları, çocukların neyi göreceğini, neyi tıklayacağını ve ne zaman duraksayacağını belirleyen, büyük ölçüde görünmez tasarım tercihleri üretmektedir (Xie, 2025; Helberger ve diğerleri, 2022).

Davranışsal ekonomi literatürü, tercih ve kararların yalnızca rasyonel değerlendirmelerle değil, aynı zamanda çevresel ipuçları, varsayılan seçenekler ve sunum biçimleri tarafından da şekillendirildiğini göstermektedir (Thaler ve Sunstein, 2008). Çevrimiçi bağlamda "çevrimiçi seçim mimarisi" olarak adlandırılan bu yapı, dijital tasarım unsurlarının kullanıcı davranışları üzerindeki sistematik etkilerini ifade etmektedir (Davranışsal Öngörüler Ekibi, 2022). Çocuklara yönelik dijital pazarlamada bu mimarinin büyük ölçüde yapay zeka tarafından dinamik olarak optimize edilmesi, davranışsal savunmasızlık yaratan yeni risk alanları oluşturmaktadır (Birleşmiş Milletler Ticaret ve Kalkınma Konferansı [UNCTAD], 2022; Helberger ve diğerleri, 2022).

Bu çalışma, çocukların maruz kaldığı algoritmik seçim mimarisini gelişimsel psikoloji ve çift sistem karar verme modelleriyle ilişkilendirerek kavramsallaştırmayı ve bu mimarinin çocuk özerkliği, mahremiyeti ve dijital iyi oluş üzerindeki etik sonuçlarını tartışmayı amaçlamaktadır. Çalışmanın üç temel sorusu şunlardır: (1) Algoritmik yönlendirme çocuk dijital ortamlarında nasıl bir seçim mimarisi olarak işlev görmektedir? (2) Çocukluk ve ergenliğin hangi gelişimsel özellikleri bu yönlendirmelere karşı duyarlılığı artırmaktadır? (3) Bu sürecin çocuk tüketicilerin özerkliği ve dijital iyi oluşu üzerindeki etik sınırları nerede çizilmelidir?

2. Kavramsal Arka Plan

2.1. Seçim mimarisi ve dijital dürtme

Thaler ve Sunstein (2008), seçim mimarisini bireylerin kararlarını etkileyen ortam özelliklerinin toplamı olarak tanımlamakta ve küçük tasarım müdahalelerinin davranış üzerinde büyük etkiler yaratabileceğini göstermektedir. Dijital ortamlarda bu yaklaşım, menü yapıları, varsayılan ayarlar, bildirim tasarımları ve görsel hiyerarşiler gibi unsurlar aracılığıyla "dijital dürtme" biçiminde karşımıza çıkmaktadır (Helberger ve diğerleri, 2022; Davranışsal Öngörüler Ekibi, 2022).

Çevrimiçi seçim mimarisi üzerine yapılan çalışmalar, aldatıcı tasarım örüntülerinin, manipülatif arayüzlerin ve veri temelli kişiselleştirme tekniklerinin özellikle savunmasız tüketici grupları üzerinde güçlü etkilere sahip olabileceğini ortaya koymaktadır (UNCTAD, 2022). Çocuklar, bilişsel ve duygusal gelişim düzeyleri gereği bu tür tasarımsal nüansları fark etmekte ve sorgulamakta yetişkinlere kıyasla daha dezavantajlı konumdadır (Nairn ve Fine, 2008; Pechmann ve diğerleri, 2005).

2.2. Çift sistem kuramı ve çocuk karar verme süreçleri

Çift sistem kuramı, karar verme süreçlerini hızlı, sezgisel ve otomatik "Sistem 1" ile daha yavaş, analitik ve kontrol odaklı "Sistem 2" arasında ayrıştırır (Kahneman, 2011; Evans ve Stanovich, 2013). Çocukluk ve ergenlik döneminde Sistem 1 süreçlerinin göreli baskınlığı, duygusal ve sosyal ipuçlarına yüksek duyarlılık ve anlık ödüllere yönelimle karakterize edilmektedir (Pechmann ve diğerleri, 2005).

Nörogelişimsel çalışmalar, prefrontal korteks gibi yönetici işlevlerden sorumlu beyin bölgelerinin ergenlik sonuna kadar tam olgunluğa ulaşmadığını; buna karşılık ödül ve duygusal tepkisellik sistemlerinin daha erken yaşta yüksek aktivite gösterdiğini ortaya koymaktadır (Casey, Getz ve Galván, 2008). Bu dengesizlik, özellikle duygusal olarak yüklü veya sosyal onay içeren uyarıcılara karşı dürtüsel tepkileri artırmakta ve algoritmik yönlendirmeye açık bir bilişsel zemin oluşturmaktadır (Nairn ve Fine, 2008).

2.3. Dijital reklamcılık ve çocukların savunmasızlığı

Dijital reklamcılık alanındaki çalışmalar, çocuklara ve ergenlere yönelik pazarlamanın çok kanallı, gömülü ve kişiselleştirilmiş biçimler aldığını göstermektedir (AAP, 2020; Güvenli Web, 2023). Sponsorlu içerik, etkileyici pazarlama, oyun içi markalı öğeler ve davranışsal hedefleme gibi formatlar, reklam ile içerik arasındaki sınırları bulanıklaştırmaktadır (Çocuklar ve Ekranlar Vakfı, 2024).

Amerikan Pediatri Akademisi, çocukların ikna niyetini ayırt etme ve reklam mesajlarını eleştirel değerlendirme becerilerinin gelişimsel olarak sınırlı olduğunu; gömülü ve kişiselleştirilmiş reklam formatlarına karşı özellikle duyarlı olduklarını vurgulamaktadır (AAP, 2020). Nairn ve Fine (2008), geleneksel "ikna bilgisi" tartışmasının ötesine geçerek, çocuk reklamcılığının giderek daha fazla örtük duygusal çağrışımlara ve otomatik süreçlere yaslandığını öne sürmektedir.

3. Yöntem: Tematik Sentez Yaklaşımı

Bu çalışma, kavramsal bir inceleme olarak tasarlanmış ve üç literatür alanını tematik sentez yöntemiyle bütünleştirmiştir: (1) davranışsal ekonomi ve seçim mimarisi, (2) gelişimsel psikoloji ve çocuk karar verme süreçleri, (3) yapay zeka destekli pazarlama ve algoritmik yönlendirme etiği (Thaler ve Sunstein, 2008; Kahneman, 2011; Xie, 2025). Literatür taraması; Scopus, Web of Science, Google Scholar ve PubMed veri tabanlarında "algorithmic nudging", "choice architecture", "children AND digital marketing", "developmental vulnerability AND persuasive technology" anahtar sözcükleriyle gerçekleştirilmiş; 2015–2025 yılları arasında yayımlanan, çocuklara ve savunmasız tüketicilere odaklanan politika raporları ve kılavuzlar da değerlendirmeye dahil edilmiştir (UNCTAD, 2022; Ekonomik İşbirliği ve Kalkınma Örgütü [OECD], 2025; Birleşmiş Milletler Çocuklara Yardım Fonu [UNICEF], 2021).

Bulgular, tematik kodlama yoluyla analiz edilmiş ve "seçim mimarisi", "algoritmik dürtme", "gelişimsel savunmasızlık" ve "davranışsal açık" gibi üst düzey temalar altında yeniden yapılandırılmıştır (Davranışsal Öngörüler Ekibi, 2022; Helberger ve diğerleri, 2022). Kodlama sürecinde iki araştırmacı bağımsız olarak çalışmış, görüş ayrılıkları görüşme yoluyla giderilmiştir.

4. Algoritmik Yönlendirme ve Çocuk Ortamlarında Seçim Mimarisi (Birinci Katman)

4.1. Öneri algoritmaları ve varsayılan yollar

Yapay zeka destekli öneri sistemleri, çocukların tükettiği içerik çeşitliliğini ve sırasını belirleyen temel seçim mimarisi bileşenlerinden biridir (Xie, 2025). Otomatik oynatma, sonsuz kaydırma ve "sıradaki öneri" tasarımları, çocukların kararlarını varsayılan seçeneğe yönlendiren güçlü dürtüler üretmektedir (Davranışsal Öngörüler Ekibi, 2022).

Çevrimiçi seçim mimarisi üzerine yapılan incelemeler, varsayılanların değiştirilmesinin davranışta büyük farklar yaratabildiğini göstermektedir (Helberger ve diğerleri, 2022). Çocuk kullanıcılar için varsayılan olarak açık bırakılan bildirimler, kişiselleştirilmiş reklam izni ve veri paylaşımı seçenekleri, bilinçli rızadan çok algoritmik olarak üretilmiş bir "davranışsal onay" mekanizmasına dayanmaktadır (UNCTAD, 2022; Uluslararası Mahremiyet Uzmanları Derneği [IAPP], 2024).

4.2. Oyunlaştırma, ödül sistemleri ve mikro hedefleme

Oyunlaştırma unsurları, özellikle çocuklara yönelik platformlarda sıklıkla kullanılan bir algoritmik yönlendirme aracıdır (Güvenli Web, 2023). Puanlar, rozetler, günlük giriş ödülleri ve zaman sınırlı kampanyalar, Sistem 1'in anlık ödül duyarlılığını hedef alarak çocukların platformda kalma süresini ve harcama davranışlarını artırmaktadır (Pechmann ve diğerleri, 2005).

Bu mekanizmalar, veri güdümlü mikro hedefleme ile birleştiğinde, çocukların geçmiş davranışlarına göre hassas şekilde ayarlanmış dürtmeler üretir (Xie, 2025). Özellikle beslenme, oyun içi satın alma ve sosyal karşılaştırma temalı içeriklerde bu tür algoritmik dürtmelerin uzun vadeli sağlık ve iyi oluş üzerindeki etkilerine yönelik kaygılar artmaktadır (AAP, 2020; Çocuklar ve Ekranlar Vakfı, 2024).

4.3. Algoritmik dürtme ve aldatıcı tasarım örüntüleri

Algoritmik dürtmeler, kullanıcıların seçenek seti içinde belirli yönlerde hareket etmelerini sağlayan, çoğu zaman görünmez mikro müdahalelerdir (Helberger ve diğerleri, 2022). Aldatıcı tasarım örüntüleri ise, tasarımın kullanıcıların zararına olacak biçimde —örneğin abonelikten çıkışı zorlaştırmak, veri paylaşımını varsayılan hale getirmek gibi— yapılandırılmasını ifade eder (UNCTAD, 2022).

Çocuk bağlamında bu pratikler, örneğin "itiraz edersen oyun durur" şeklinde kurgulanan onay ekranları veya reklam izlemeyi "görev" haline getiren mekanikler üzerinden ortaya çıkmaktadır

(Güvenli Web, 2023). Bu tür tasarımlar, çocukların hem bilişsel hem de duygusal savunmasızlığını istismar eden davranışsal açıklar üretmektedir (Nairn ve Fine, 2008; UNCTAD, 2022).

5. Çift Sistem Kuramı Işığında Davranışsal Açıklar (İkinci Katman)

5.1. Sistem-1 hedeflemesi ve örtük ikna

Çift sistem modelleri, tüketici kararlarının önemli bir kısmının bilişsel tasarruf, sezgisel yargılar ve duygusal çağrışımlarla verildiğini ortaya koymuştur (Kahneman, 2011; Evans ve Stanovich, 2013). Nairn ve Fine (2008), çağdaş çocuk reklamcılığının açık mesajlardan çok örtük duygusal ve sosyal çağrışımlara yaslanan formatlar üzerinden ilerlediğini ve bu nedenle Sistem 1 süreçlerini yoğun biçimde hedeflediğini savunmaktadır.

Algoritmik yönlendirme, çocukların sosyal onay, aidiyet ve statü arayışı gibi Sistem 1 hassasiyetlerini kullanarak, "herkes bunu oynuyor", "arkadaşların bunu satın aldı" veya "kaçırma" temelli mesajlarla tüketim davranışlarını şekillendirebilmektedir (Pechmann ve diğerleri, 2005; Çocuklar ve Ekranlar Vakfı, 2024).

5.2. Gelişimsel açıdan olgunlaşmamış Sistem 2

Gelişimsel psikoloji bulguları, çocukların ikna niyeti ve ticari mesajları anlama kapasitesinin yaşla birlikte artmasına rağmen, karmaşık ve gömülü reklam formatlarına karşı ergenlik döneminde bile yüksek savunmasızlığın sürdüğünü göstermektedir (Pechmann ve diğerleri, 2005; AAP, 2020). Özellikle dikkat dağıtıcı unsurların yoğun olduğu, hızlı akan içerik ortamlarında Sistem 2 devreye girme fırsatı bulamadan Sistem 1 kararları baskın hale gelmektedir (Kahneman, 2011; Nairn ve Fine, 2008).

Bu nedenle, yapay zeka destekli pazarlama sistemlerinde Sistem 2'nin devreye girmesini gerektiren açık ve yavaşlatıcı bilgilendirme mekanizmalarının eksikliği, çocuklar için kalıcı davranışsal açıklar anlamına gelmektedir (Helberger ve diğerleri, 2022; UNCTAD, 2022).

6. Çocuk Tüketicinin Özerkliği ve Dijital İyi Oluşu (Üçüncü Katman)

6.1. Özerklik ve bilgilendirilmiş tercih sorunu

Davranışsal özerklik, bireyin kendi değerleri doğrultusunda, yeterli bilgi ve düşünme süresiyle karar verebilmesi anlamına gelir (Thaler ve Sunstein, 2008). Çocuk bağlamında bilgilendirilmiş tercih, hem bilişsel anlama kapasitesi hem de sosyal baskıların farkına varma becerisiyle sınırlıdır (Pechmann ve diğerleri, 2005).

Yapay zeka destekli seçim mimarisi, çocuklara çoğu zaman tek bir "doğal yol" sunarak alternatiflerin fark edilmesini zorlaştırmakta, böylece özerk tercih alanını daraltmaktadır (Helberger ve diğerleri, 2022). Bu durum, hukuken rıza alınmış olsa bile davranışsal açıdan anlamlı

bir özerkliğin gerçekleşmediği bir "davranışsal rıza" düzeni üretmektedir (UNCTAD, 2022; UNICEF, 2021).

6.2. Dijital iyi oluş ve uzun vadeli etkiler

Dijital iyi oluş, bireyin dijital teknolojilerle ilişkisinin yaşam kalitesini destekleyecek şekilde dengeli ve sağlıklı olması durumu olarak tanımlanmaktadır (OECD, 2025). Son çalışmalar, yoğun algoritmik içerik akışlarının çocuk ve ergenlerin uyku kalitesi, beden algısı, kaygı ve depresyon düzeyleriyle ilişkili olabileceğine işaret etmektedir *(yazar bilgisi belirtilmeli; Asian Journal of Psychiatry, 2025)*.

Çocuklara yönelik manipülatif dijital pazarlama uygulamaları üzerine yürütülen araştırmalar, özellikle beslenme ve oyun odaklı içeriklerin sağlıksız davranış örüntülerini pekiştirebileceğini göstermektedir *(AB Komşulukları [EUNeighbours], 2025 — akademik kaynak olarak zayıf; mümkünse hakemli makale ile değiştirilmelidir)*. Bu bağlamda algoritmik yönlendirmenin yalnızca kısa vadeli tüketim tercihlerini değil, uzun vadeli sağlık ve refah göstergelerini de etkileyen kritik bir faktör olduğu anlaşılmaktadır (AAP, 2020; Çocuklar ve Ekranlar Vakfı, 2024).

7. Şeffaflık, Hesap Verebilirlik ve Politika Çıkarımları

Algoritmik sistemlerde şeffaflık, kullanıcıların hangi veri temelli mekanizmalarla yönlendirildiklerini anlayabilmeleri için temel bir ilkedir (UNICEF, 2021; IAPP, 2024). Ancak çocuklara yönelik dijital pazarlama ortamlarında açıklamalar genellikle yetişkin diliyle ve uzun kullanım koşulları biçiminde sunulmakta, çocukların anlamlı şekilde yararlanabileceği "yaşa uygun şeffaflık" mekanizmaları sınırlı kalmaktadır (UNCTAD, 2022).

Hesap verebilirlik ise, platformların ve reklamverenlerin çocukları hedefleyen algoritmik tasarımlarının sonuçlarından sorumlu tutulmasını gerektirir (UNICEF, 2021; OECD, 2025). Bu kapsamda, manipülatif dijital pazarlama pratiklerinin tanımlanması, ölçülmesi ve sınırlandırılması için daha net düzenleyici çerçevelere ihtiyaç bulunmaktadır *(AB Komşulukları [EUNeighbours], 2025 — akademik kaynak olarak zayıf)*. Ayrıca çocuklara yönelik tasarımlarda "varsayılan olarak gizlilik" ve "güvenli tasarım" ilkelerinin benimsenmesi, davranışsal açıkları azaltmada kritik önemdedir (IAPP, 2024; Çocuklar ve Ekranlar Vakfı, 2024).

8. Sonuç

Bu çalışma, yapay zeka destekli pazarlama ekosistemlerinde çocukların maruz kaldığı algoritmik seçim mimarisini, çift sistem kuramı ve gelişimsel psikoloji perspektiflerinden kavramsallaştırmıştır. Çocukların henüz olgunlaşmamış yönetici işlevleri ve yüksek duygusal/sosyal duyarlılıkları nedeniyle, Sistem 1'i hedefleyen algoritmik dürtmeler karşısında

belirgin davranışsal açıklara sahip oldukları savunulmuştur (Nairn ve Fine, 2008; Pechmann ve diğerleri, 2005).

Algoritmik yönlendirmenin yalnızca bireysel tercihleri değil, aynı zamanda çocukların uzun vadeli dijital iyi oluşunu da etkileyen yapısal bir mesele olduğu; bu nedenle şeffaflık, hesap verebilirlik ve gelişimsel uygunluk ilkeleri temelinde yeniden düşünülmesi gerektiği vurgulanmıştır (UNICEF, 2021; OECD, 2025). Politikacılar, araştırmacılar ve sektör paydaşları için bu çalışma, çocuk tüketicilerin davranışsal açıklarını merkeze alan hak-temelli bir kavramsal çerçeve sunmaktadır.

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EFFECT OF FOLIAR APPLICATION OF BORON AND ZINC ON COTTON QUALITY CHARACTERISTICS-II *

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ABSTRACT

This study was carried out to determine the fiber technological characteristics of different Zinc (Zn) and Boron (B) applications in cotton. The study was carried out as the Randomized Complete Blocks Design with four replications under Siirt ecological conditions at 2022. In the study, MAY 455 cotton variety was used as materials. The study included 7 different (Control, Zn 45, Zn (45+60), Zn (45+60+75), B 45, B (45+60), B (45+60+75)) applications. According to the results of the study, no significant difference was found between the applications in terms of all the fiber quality characteristics (fiber length, fiber fineness, fiber strength, spinning consistency index, uniformity, elongation, short fiber index, moisture, brightness and yellowness) examined. These results show that zinc and boron application did not cause any difference in fiber quality. However, the results of this study do not coincide with the results obtained in previous studies, which indicated that zinc and boron caused significant differences in fiber quality characteristics. These results may be due to the environmental conditions in which the experiment was conducted and the materials used. However, continuing the study for at least one more year is important for making more definitive recommendations.

Keywords: Plant nutrient, boron, zinc, fiber quality properties, cotton

* This study is derived from Burhan URAZ's master's thesis.

YAPRAKTAN BOR VE ÇİNKO UYGULAMALARININ PAMUKTA KALİTE ÖZELLİKLERİNE ETKİSİ-II *

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ÖZET

Bu çalışma farklı Çinko ve Bor uygulama yöntemlerinin pamukta teknolojik özellikler üzerine olan etkisini belirlemek amacıyla yürütülmüştür. Çalışma 2022 yılında Siirt Üniversitesi Ziraat Fakültesi deneme alanında tesadüf blokları deneme desenine göre 4 tekrarlamalı olarak yürütülmüş ve denemede materyal olarak May 455 pamuk çeşidi ve yapraktan bor ve çinko mikro bitki besin elementleri kullanılmıştır. Denemede 7 farklı uygulama (Kontrol, Zn 45, Zn (45+60), Zn (45+60+75), Bor 45, Bor (45+60), Bor (45+60+75)) yer almıştır. Çalışmadan elde edilen sonuçlara göre lif uzunluğu, lif inceliği, lif kopma dayanıklılığı, iplik olabilirlik indeksi, üniformite, lif kopma uzaması, kısa lif indeksi, nem, parlaklık ve sarılık olmak üzere incelenen lif kalite özellikleri bakımından uygulamalar arasında önemli bir farklılık elde edilmemiştir, bu sonuçlar çinko ve bor uygulamasının lif kalitesinde herhangi bir farklılığa neden olmadığını ortaya koymuştur, ancak bu çalışmadan elde edilen sonuçlar önceki çalışmalarda elde edilen ve çinko ve bor'un lif kalite özelliklerinde önemli farklılıklar elde edildiğine ilişkin sonuçlar ile örtüşmemektedir. Bu sonuçlar denemenin yürütüldüğü çevre şartları ve kullanılan materyalden kaynaklanmış olabilir. Ancak çalışmanın en az bir yıl daha yürütülmesi daha net öneri yapılması bakımından önemlidir.

Anahtar Kelimeler: Bitki besin elementi, bor, çinko, lif kalite özellikleri, pamuk

* Bu çalışma Burhan URAZ'ın yüksek lisans tezinden türetilmiştir.

1. Giriş

Pamuk, tropikal ve subtropikal bölgelerde yaygın olarak yetiştirilen, hayati öneme sahip küresel bir lif bitkisidir. Tekstil endüstrisinde çok önemli bir rol oynar ve çok çeşitli ürünler için hammadde sağlar. Pamuğun önemi, ekonomik değerinin ötesine uzanır; zira dünya çapında milyonlarca çiftçinin geçim kaynağına da önemli ölçüde katkıda bulunur (Wahid ve ark., 2020; Abbas ve ark., 2022). Pamuk (*Gossypium hirsutum* L.), yüksek adaptasyon yeteneği, iyi lif kalitesi ve yüksek verimi nedeniyle dünya çapında en önemli lif bitkilerinden biridir. Beyaz altın olarak da bilinen pamuk, önemli bir gelir kaynağı ve tekstil endüstrisi için en önemli hammadde kaynağıdır. Pamuk verimi, dengesiz beslenme, hormonlar, çiçek ve koza dökülmesi gibi birçok nedenden etkilenmektedir. Verimlilikteki azalmanın nedenleri arasında özellikle mikro besin maddelerinin azalması, gübrelerin dengesiz uygulanması ve koza dökülmesi, koza kuruması, yaprak kızarması gibi fizyolojik bozuklukların ortaya çıkması yer almaktadır. Bunlar arasında makro ve mikro besin maddelerinin dengesiz kullanımı en büyük sorunlardan bir tanesidir (Hebbar ve ark., 2007).

Pamukta kalite oldukça önemlidir. Kaliteyi artırmanın birçok yolu vardır. Bu yollardan biri, besin maddelerinin yapraktan uygulanması gibi uygulanabilir yönetim uygulamalarını uyarlayarak ürün metabolizmasını hızlandırmaktır. Yapraktan gübreleme, anlık tepki, daha kolay uygulama, toprak gübrelemesinin desteklenmesi, besin eksikliklerinin düzeltilmesi, girdi maliyetinin azaltılması ve besin alımının iyileştirilmesi gibi birçok avantajla ürün büyümesini arttırmanın etkili yollarından biridir (Fageria ve ark., 2009). Pamuk diğer bitkilerde olduğu gibi üç temel makro bitki besin elementi olan azot, fosfor ve potasyuma gereksinim duyar. Yeryüzü toprakları bitki besin elementlerini barındırır ancak bu miktar optimum üretim için yeterli olmamaktadır. İlave olarak verilen gübreler, doğal olarak mevcut olan bitki besin elementleri ile ihtiyaç duyulanlar arasındaki farkı kapatır.

Pamuk üretiminde makro bitki besin elementlerinin yanı sıra bor, çinko, molibden gibi mikro besin elementlerine de gereksinim duyulur. Etkili bir gübreleme için toprak analizi yaptırmak önem arz etmektedir. Genel olarak bir dekarlık bir alandan 400 kg pamuk hasat edilerek topraktan uzaklaştırılır. Hasat edilen ürün, bitkinin büyümesi sırasında topraktan alınan besin maddelerini içerir ve topraktaki besin maddeleri yerine konmadığı sürece sürdürülebilir bir üretim söz konusu olamaz. Yavaş ve kontrollü salınımlı gübreler, stabilize azotlu gübreler, sıvı gübrelerin yer altına enjeksiyonu ve yapraktan uygulanması gibi verimliliği artırılmış gübrelerin kullanımı giderek yaygınlaşmakta ve gübrelerin kullanım verimliliğini artırmaktadır (Jordan and Wakelyn 2010).

Bor (B), bitkiler tarafından düşük miktarlarda ihtiyaç duyulan temel bir besin maddesidir (Hussain ve ark., 2012). Bitki büyüme ve gelişmesinde birçok hayati rol oynar. Bitkilerin üretimindeki önemli sınırlamalardan biri, özellikle Boron (B) olmak üzere mikro besin maddelerinin yetersiz kullanımıdır; bu da pamuğun büyüme, verim ve kalite özelliklerine önemli bir risk oluşturmaktadır (Atique-ur-Rehman ve ark., 2022). Bitkilerin fizyolojik ve biyokimyasal süreçleri B eksikliğine karşı hassasiyet gösterirken, kabul edilebilir seviyelerin üzerindeki konsantrasyonlar toksik etkiler nedeniyle bitki büyüme ve gelişiminde azalmaya neden olur (Behera ve ark., 2023). Bor, çiçeklenmenin başlatılmasında ve tohum ve meyve üretiminde aktif rol oynar. Ayrıca, B uygulamasının, çoğunlukla kök ve çiçek gelişiminin seviyelerini

düzenleyerek, bitkilerde P alımını ve entegrasyonunu artırdığı gösterilmiştir (Mehboob ve ark., 2022). Boron, polen oluşumunu kolaylaştırmada ve döllenme süreçlerini hızlandırmada çok önemli bir role sahiptir. Bu, bitkilerin üreme organlarındaki ideal hormon seviyelerinin düzenlenmesi yoluyla sağlanır ve sonuç olarak tohum gelişimi, büyüme ve lif kalitesi iyileşir (Rashidi ve Seilsepour, 2009). Ayrıca, optimal seviyenin üzerinde aşırı B kullanımı, bitkilerin sağlığı üzerinde zararlı etkilere sahiptir ve ürün nekrozuna ve kuru madde birikiminin azalmasına neden olur. B eksikliği fotosentezi ve yapraklardan meyvelere karbonhidrat taşınmasını engeller (Zhao ve Oosterhuis, 2002). Dahası, B eksikliği olgunlaşma süreci boyunca koza ve çiçeklerin dökülmesine neden olarak verimin azalmasına ve lif kalitesinin bozulmasına yol açar (Sankaranarayanan ve ark., 2010). Pamuğun gelişimi için vazgeçilmez olması ve bitki içinde hareket etme yeteneğinin sınırlı olması nedeniyle, B varlığı yaşam döngüsünün tamamı boyunca önemlidir (de Oliveira ve ark., 2006). B eksikliği, mevcut karbonhidrat miktarında azalmaya ve kozaların dökülmesine yol açar (Zhao ve Oosterhuis, 2003). Borun temel işlevi polen kısırlığını azaltmaktır; bu da çiçek sayısını artırır ve dolayısıyla ürün verimliliğini yükseltir. Çok sayıda çalışma, farklı ürünler için B dozlarını optimize etmiştir. Bununla birlikte, yapraktan uygulanan borun pamukta koza tutunması ve lif kalitesi özellikleri üzerindeki etkisi nadiren araştırılmaktadır.

Çinko, mavimsi beyaz bir metal olup, yeryüzü kabuğunun yaklaşık %0,02'sini oluşturan 23. en büyük elementtir (Hussain ve ark., 2022). Temel bir element olan çinko, pamuğun farklı büyüme, metabolik ve üreme aşamalarında rol oynar (Anik ve ark., 2023). Pamuk bitkilerinde çeşitli metabolik süreçlerde yer alan 300'den fazla enzimin yapısal ve işlevsel bileşenidir (Wang ve ark., 2020). Çinko, tohum çimlenmesi (Li ve ark., 2004), su ilişkileri ve su kullanım verimliliği (Anik ve ark., 2023), ozmolit sentezi (Hatam ve ark., 2020), stomatal düzenleme (Sarwar ve ark., 2022), klorofil sentezi ve fotosentetik verimlilik (More ve ark., 2018), antioksidan savunma sistemi (Çakmak 2000), protein metabolizması (Sawan ve ark., 2001; Lacerda ve ark., 2018), membran stabilizasyonu (Ghanepour ve ark., 2015) ve üreme gelişimi (Sadeghzadeh, 2013) gibi süreçlerdeki rolü aracılığıyla bitki büyüme ve gelişimini etkilediği bilinmektedir. Düşük çinko kullanım verimliliği sorunu, alkali kireçli topraklarda çinkonun yapraktan uygulanmasıyla giderilebilir (Doolette ve ark., 2018). Bitkilerde çinko eksikliğinin belirtileri boğum aralarının kısalması, yaprak alanının azalması, bitki boyutunun küçülmesi, rozetlerin ortaya çıkması, sararma ve nekroz ile ortaya çıkar (Oliveira ve ark., 2023). Ahmed ve ark., (2020)'ye göre, yüksek çinko adsorpsiyon kapasitesine sahip topraklarda pamuk büyümesini ve verimini artırmak için yapraktan uygulama daha etkili olabilir. Çinko'nun yeterli düzeyde düzenlenmesi, pamuğun optimum büyümesi, verimi ve lif kalitesi için kritik öneme sahiptir (Çeçen ve Karademir, 2022).

2. Materyal ve Yöntem

Materyal

Çalışma Siirt Üniversitesi Ziraat Fakültesi Tarla Bitkileri Anabilim Dalı deneme alanında 2022 yılında kurulmuştur. Denemede May 455 pamuk çeşidi materyal olarak kullanılmıştır. Bor kaynağı olarak “Actıv Bor” ve çinko kaynağı olarak “Zincon” kullanılmıştır.

Deneme alanının toprak ve iklim özellikleri

Denemenin kurulduğu Siirt Üniversitesi Ziraat Fakültesi deneme alanı oldukça düşük eğime sahip, derin ve orta derin topraklardan meydana gelmiş olup, organik madde içerikleri düşüktür. Deneme alanı tuzluluk yönünden referans değerlerin oldukça altında olup tuzluluk problemi yoktur. Toprak katmanları boyunca ihtiva ettikleri yüksek nispetteki kil mineralleri sebebiyle kışları genişleyip şişmekte, yaz aylarında ise toprak yüzeyinden neredeyse 1 m derinliğinde çatlaklar oluşmaktadır.

Deneme sahasından ekim öncesi usulüne uygun bir şekilde toprak numuneleri alınarak bazı toprak özellikleri saptanmıştır. Saptanan özellikler Tablo 2.1'de verilmiştir.

Tablo 2.3. Deneme alanının toprak özellikleri

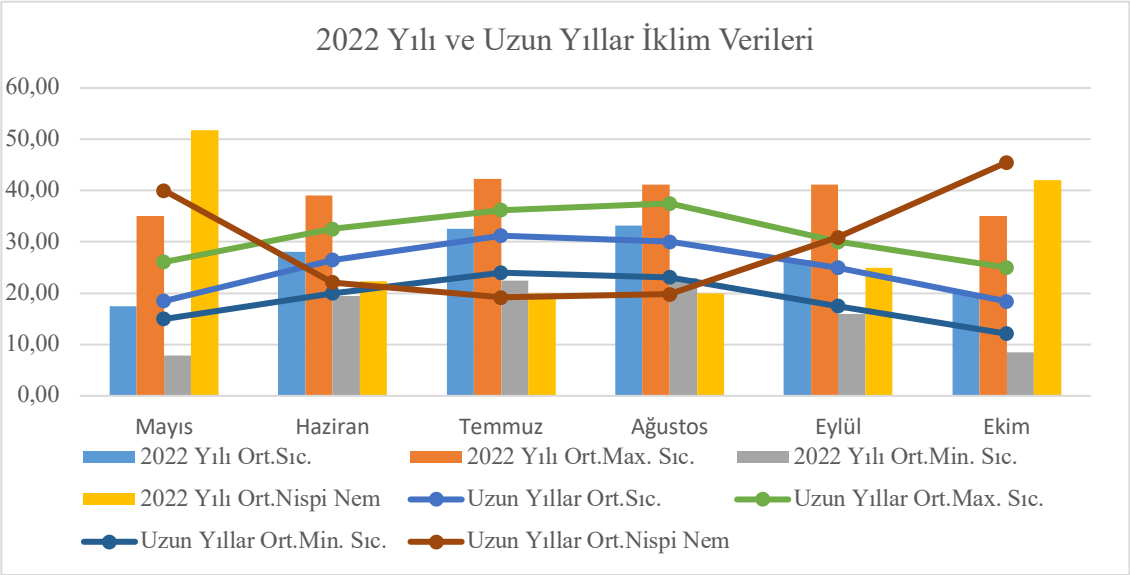
Tekstür	**Kil**	**Açıklama**
pH	7,98	Hafif alkali
EC (mS/cm)	0,363	Tuzsuz
Kireç (%$CaCO_3$)	13,02	Kireçli
Org.madde (%)	1,31	Düşük
N (%)	0,082	Düşük
P (ppm)	7,47	Az
K (me/100g)	0,98	Fazla
Fe (ppm)	5,70	Yeterli
Cu (ppm)	2,63	Yeterli
Zn (ppm)	0,23	Az
Mn (ppm)	6,04	Az

Kaynak: Siirt Üniversitesi Bilim ve Teknoloji Uygulama ve Araştırma Merkezi Laboratuvarı

Tablo 2.1. incelendiğinde, ekimden önce alınan toprak numunelerinde, bünyenin killi, pH hafif bazik, elektriksel iletkenlik referans değerlerin altında tuzsuz, kireç oranı yüksek, organik maddece fakir, azot içeriği bakımından düşük, fosfor, çinko ve mangan içeriği yönünden az, demir içeriği ve bakır yönüyle yeterli, potasyum içeriği bakımından ise fazla olarak tespit edilmiştir.

Siirt ilinde yazlar sıcak ve kurak olup kışlar çok soğuk ve genelde parçalı bulutludur. Yıl içerisinde sıcaklık normalde -2°C ile 37°C arasında değişiklik göstermektedir. Kışları -8°C'nin altında düşebilirken, yazları 40°C'nin üzerinde sıcaklık yaşanabilmektedir (Url-1).Haziran ve Ekim ayları arasında genellikle yağış görülmemektedir. Gece ile gündüz arasındaki sıcaklık farkı yüksektir. Rüzgârlar geceleri doğu ve kuzeydoğudan, gündüzleri ise güney ve güneybatıdan esmekte iken kışın ise genellikle kuzey ve kuzeybatıdan esmektedir. Denemenin yürütüldüğü 2022 yılına ve uzun yıllara ait sıcaklık değerleri Tablo 2.2'de verilmiştir.

Tablo 2.4. Denemenin yürütüldüğü 2022 yılı ile uzun yıllar iklim verileri



* Meteoroloji Genel Müdürlüğü, Uzun Yıllar Ortalaması: 1950-2015

Tablo 2.2 incelendiğinde denemenin yürütüldüğü 2022 yılı ortalama sıcaklık değerlerinin Mayıs ayı hariç diğer aylarda uzun yıllar ortalamasının üzerinde olduğu, ortalama maksimum sıcaklığın tüm aylarda uzun yıllar sıcaklıklarından daha yüksek olduğu Eylül ve Ekim aylarında bu farkın 10 ºC' ye kadar ulaştığı, ortalama minimum sıcaklıkların Ekim ayı dışında genel olarak paralel olduğu ancak Ekim ayında bu değerin uzun yıllar ortalamasının 3,5 ºC altında kaldığı nispi nemin ise uzun yıllar ile paralel seyrettiği izlenebilmektedir.

Toprak Hazırlığı ve Ekim

Denemenin kurulduğu tarla alanı sonbaharda pullukla derin bir şekilde sürülmüş ilkbaharda ekimden önce kültivatör ile yüzlek bir şekilde işlenmiş ve ekim yapılmadan önce 3 defa tapan çekilerek deneme alanı pamuk ekimi için uygun bir duruma getirilmiştir. Deneme alanı ekime hazır hale getirildikten sonra parselasyon yapılmıştır. Çalışmada ekim işlemleri mini ekim makinesi ile yapılmıştır, ekimde her parselin boyu 6 m ve 4 sıradan oluşturulmuştur. Her bir parselin genişliği 4 x 0,7 m = 2.8 m olup, bloklar arasında 2 m aralık bırakılmıştır. Buna göre araştırmanın eni 28 m, uzunluğu ise 30 m olmak üzere, toplam alan 19,6 m x 30 m = 588 m2 olmuştur.

Sıra arası uzaklık ekimde 0,70 m sabit tutulmuş, sıra üzeri uzaklık ise seyreltme yapılarak 10-15 cm olacak şekilde ayarlanmıştır. Ekimde her bir parsel alanı 6 m x 4 sıra x 0,70 m: 16,8 m2 olmuştur. Deneme alanından ekim öncesinde toprak örnekleri alınarak merkezi laboratuvarda toprak analizleri yapılmış ve bitkinin gereksinim duyduğu gübre miktarı belirlenmiştir. Ekim esnasında bitki için gerekli olan azotun yarısı (hızlı hareket ettiği için) ile fosforun tamamı (geç yarayışlı hale geldiği için) uygulanmış, geriye kalan azotun ikinci yarısı ise taraklanma döneminde ilk sulamadan önce ara çapa yapıldığı esnada kombine gübre makinesi ile verilmiştir.

Siirt Üniversitesi Ziraat Fakültesi deneme alanlarında 2022 yılı pamuk yetiştirme döneminde tesadüf blokları deneme deseninde göre 4 tekerrürlü olarak kurulan araştırmada kontrol dâhil 7

farklı uygulama yapılmıştır. Uygulamalara ilişkin ayrıntılar aşağıda belirtilmiştir. Kontrol uygulamasında bölgede üreticiler tarafından uygulanan standart gübreleme (16 kg/da azot + 8 kg/da fosfor) uygulanmıştır. Diğer uygulamalar ise kontrole ek olarak yapraktan şarjlı sırt pülverizatörü ile püskürtülmek suretiyle uygulanmıştır.

Uygulamalar

2. Kontrol Geleneksel gübreleme; 16 kg/da N, 8 kg/da P_2O_5
3. Zn (45) Ekimden 45 gün sonra Zn uygulaması
4. Zn (45 + 60) Ekimden 45 ve 60. gün sonra olmak üzere 2 kez uygulama
5. Zn (45 + 60 + 75) Ekimden 45, 60 ve 75. gün sonra olmak üzere 3 kez uygulama
6. B (45) Ekimden 45 gün sonra B uygulaması
7. B (45 + 60) Ekimden 45 ve 60. gün sonra olmak üzere 2 kez uygulama
8. B (45 + 60 + 75) Ekimden 45, 60 ve 75. gün sonra olmak üzere 3 kez uygulama

Bakım İşlemleri

Bitkiler 15 cm boya eriştiklerinde sıra üzeri uzaklık 10-15 cm olacak şekilde seyreltilmiş, deneme boyunca 3 kere el çapası, 2 kere makina çapası geçmiştir. Bitki gelişim periyodu süresince yabancı ot ve zararlı kontrolleri fakültemiz bitki koruma bölümü ile işbirliği halinde yapılmıştır. Denemenin alanına bölgede bazı yıllar epidemi yapan "Dikenli kurt" ve bölgede hemen hemen her pamuk üretim sezonunda görülmekte olan "Yeşil kurt"a karşı olmak üzere feromon tuzaklar konulmuştur. Bitki koruma bölümü uzman hocalarının önerileri doğrultusunda denemin yürütüldüğü pamuk üretim sezonunda zararlı popülasyonu eşik değeri geçmediği için ilaçlama yapmaya gerek duyulmadığı için ilaçlı mücadele yapılmamıştır. Denemede her parsele etiket takılarak gözlem ve uygulamaların hassas yapılması sağlanmıştır. Denemede basınçlı sulama sistemlerinden en verimli sulama yöntemi olan damla sulama sistemi kullanılmıştır. Sulamalarda bitkinin su tüketimi dikkate alınarak sulama programı planlanmıştır. Sulamaya taraklanma döneminde başlanmış ve kozaların % 10'u açtığında sonlandırılmıştır. Deneme süresince incelenen özellikler alt başlıklar halinde aşağıda açıklanmıştır.

Lif Teknolojik Analizlerinin Belirlenmesi

Lif kalite analizleri GAP Uluslararası Tarımsal Araştırma ve Eğitim Merkezi Müdürlüğü Lif kalite analiz laboratuvarında HVI (High Volume Instrument) cihazı ile belirlenmiştir. İncelenen lif kalite özelliklerine ait ayrıntılar aşağıda belirtilmiştir.

Lif uzunluğu (mm)
Lif inceliği (micronaire)

Lif kopma dayanıklılığı (g/tex)
İplik olabilirlik indeksi (SCI)
Lif üniformite oranı (%)
Lif kopma uzaması (%)
Kısa lif oranı (%)
Lif olgunluk indeksi (%)
Nem (%)
Parlaklık (Rd)
Sarılık (+b)

Hasat

Deneme hasadında ekilen 4 sıranın sağdan ve soldan birer sıraları kenar tesiri olarak bırakılmış, ortadaki iki sıradan her sıranın başından ve sonundan 0,5 m ölçülerek hasat edilmemiş geri kalan alan hasat edilmiştir. Hasat elle 17.10.2022 tarihinde yapılmıştır.

İstatistiki Analizler

Denemeden elde edilen tüm veriler, kullanılan deneme desenine uygun olarak JUMP istatistik paket program kullanılarak analiz edilmiştir. Gruplamalar $LSD_{(0.05)}$'e göre yapılmıştır.

3. Bulgular ve Tartışma

Araştırmada incelenen özelliklerden lif uzunluğu, lif inceliği, lif kopma dayanıklılığı, iplik olabilirlik indeksi, lif üniformite oranı ve Lif Kopma Uzaması özelliklerine ilişkin ortalama değerler ve oluşan gruplamalar Çizelge 3.1' de verilmiştir.

Çizelge 3.1 İncelenen özelliklere ait ortalama değerler ve oluşan gruplamalar

Uygulama	Lif Uzunluğu (mm)	Lif İnceliği (micronair)	Lif Kopma Dayanıklılığı (g tex^{-1})	SCI	Lif Üniformite Oranı (%)	Lif Kopma Uzaması (%)
1. Kontrol	29,41	5,08	35,30	145,50	83,62	5,65
2. Zn (45)	28,93	5,47	34,05	142,25	84,60	5,82
3. Zn (45 + 60)	29,15	5,23	34,50	142,50	83,97	5,65
4. Zn (45 + 60 +75)	29,21	5,30	35,77	149,50	84,50	5,67
5. Bor (45)	28,96	5,29	32,75	136,50	83,80	5,60
6. Bor (45 + 60)	28,70	5,50	33,05	133,25	83,55	5,57
7. Bor (45 + 60 +75)	29,00	5,17	34,72	143,00	84,02	5,45
Ortalama	29,05	5,29	34,30	141,78	84,01	5,63
CV (%)	2,26	4,83	5,32	6,11	1,01	3,52
LSD (0.05)	ÖD	ÖD	ÖD	ÖD	ÖD	ÖD

*** ; % 1 seviyesinde, * ; % 5 seviyesinde önemlidir.*

Lif uzunluğu (mm) : Çizelge 3.1'de lif uzunluğu bakımından değerler incelendiğinde lif uzunluğuna ait ortalama değerlerin, 27,89 mm ile 29,41 mm arasında değişim gösterdiği; uygulamalar arasında önemli istatistiksel farklılıkların bulunmadığı ve araştırmanın genel ortalamasının 29,05 mm olduğu görülmektedir. En düşük lif uzunluğunun 28,70 mm ile 7 numaralı uygulamadan elde edildiği, en yüksek lif uzunluğunun ise 29,41 mm ile 1 no'lu uygulamadan sağlandığı görülmektedir. Bu uygulamayı 4 no'lu uygulama 29,21 mm lif uzunluğu değeri ile takip etmiştir. Lif uzunluğu bakımından tüm uygulamaların sonuçları göz önünde bulundurulduğunda çinko ve bor uygulamasının yapılmadığı kontrol uygulanması en yüksek lif uzunluğu değerini göstermiş bu uygulamayı Çinko'nun ekimden 45, 60 ve 75 gün sonra yapıldığı uygulama izlemiştir. Bu çalışmanın sonucu önceki çalışmalardan Emara (2016), Buriro ve ark.(2016), Rajput ve ark. (2016), Tekin (2011), Sankaranarayanan ve ark. (2010), Abid ve ark. (2007), Durmaz (2002), Rezaei ve Malakouti (2001)'nin elde ettiği bulgular ile uyum göstermektedir, ancak çalışmalarında yapılan uygulamalar arasında önemli farklılıklar elde etmiş olan Shah ve ark. (2017) ile Yıldırım (2003)'ün elde etmiş oldukları sonuçlar ile örtüşmemektedir.

Lif inceliği (micronaire) : Lif inceliği bakımından değerler incelendiğinde lif inceliğine ait ortalama değerlerin 5,08 ile 5,50 micronaire arasında değişim gösterdiği; uygulamalar arasında önemli istatistiksel farklılıkların bulunmadığı ve araştırmanın genel ortalamasının 5,29 micronaire olduğu görülmektedir. En düşük değerin 5,08 micronaire ile 1 no'lu uygulamadan elde edildiği, en yüksek lif inceliği değerinin ise 5,50 micronaire ile 6 no'lu uygulamadan sağlandığı görülmektedir (Çizelge 3.1). Bu çalışmanın sonucu önceki çalışmalardan Emara (2016), Buriro ve ark.(2016), Rajput ve ark. (2016), Tekin (2011), Sankaranarayanan ve ark. (2010), Abid ve ark. (2007), Durmaz (2002), Rezaei ve Malakouti (2001)'nin elde ettiği bulgular ile uyum göstermektedir, ancak çalışmalarında yapılan uygulamalar arasında önemli farklılıklar elde etmiş olan Shah ve ark. (2017) ile Yıldırım (2003)'ün elde etmiş oldukları sonuçlar ile örtüşmemektedir.

Lif kopma dayanıklılığı (g tex^{-1}) : Lif kopma dayanıklılığı bakımından değerler incelendiğinde lif kopma dayanıklılığına ait ortalama değerlerin 32,75 ile 35,77 g/tex arasında değişim gösterdiği; uygulamalar arasında önemli istatistiksel farklılıkların bulunmadığı ve araştırmanın genel ortalamasının 34,30 g/tex olduğu görülmektedir. En düşük değerin 32,75 g/tex ile 7 no'lu uygulamadan, en yüksek değerin ise 35,77 g/tex ile 4 numaralı uygulamadan sağlandığı görülmektedir (Çizelge 3.1). Bu çalışmanın sonucu önceki çalışmalardan Sankaranarayanan ve ark., (2010) ile Emara (2016)'nın elde ettiği sonuçlar ile örtüşmektedir, ancak çalışmalarında yapılan uygulamaların lif kopma dayanıklılığında önemli farklılıklara yol açtığını bildiren Rajput ve ark. (2016), Tekin (2011) ile Durmaz (2002)'nıin sonuçları ile örtüşmemektedir.

İplik olabilirlik indeksi : İplik olabilirlik indeksi yönünden elde edilen verilerin uygulamalar arasında değişmek üzere 133,25 ile 149,50 arasında değişim gösterdiği, ve uygulamalar arasında istatistiksel önem seviyesinde bir farklılığın oluşmadığı izlenebilmektedir. En düşük değer 133,25 ile 6 no'lu uygulamadan elde edilmiş, en yüksek değer ise 149,50 ile 4 no'lu uygulamadan sağlanmıştır.

Lif üniformite oranı değeri (%): Çizelge 3.1'den üniformite oranı yönünden değerlerin uygulamalar arasında değişmek üzere %83,55 ile 84,60 arasında değişim gösterdiği, ancak

uygulamalar arasında istatistiksel önem seviyesinde bir farklılığın oluşmadığı görülmektedir. En düşük değer %83,55 ile 6 numaralı uygulamadan elde edilmiştir. En yüksek değer ise %84,60 ile 2 numaralı uygulamadan sağlanmıştır. Bu çalışmanın sonucu önceki çalışmalardan Sankaranarayanan ve ark. (2010), Tekin (2011) ile Emara (2016)'nın bildirdikleri sonuçlar ile uyum içinde olmamaktadır.

Lif kopma uzaması (%): Çizelge 3.1'den lif kopma uzaması yönüyle değerlerin uygulamalar arasında değişmek üzere %5,45 ile %5,82 arasında değişim gösterdiği, ancak uygulamalar arasında istatistiksel önem düzeyinde bir farklılığın olmadığı izlenebilmektedir. En düşük değer %5,45 ile 7 numaralı uygulamadan elde edilmiştir. En yüksek değer ise %5,82 ile 2 numaralı uygulamadan elde edilmiştir.Uygulamaların genel ortalamasının %5,63 olduğu görülmektedir. Bu çalışmanın sonucu önceki çalışmalardan Sankaranarayanan ve ark., (2010)'nın ortaya koyduğu sonuçlar ile benzerlikler göstermektedir.

Araştırmada incelenen özelliklerden kısa lif oranı, olgunluk, nem, parlaklık ve sarılık özelliklerine ilişkin ortalama değerler ve oluşan gruplamalar Çizelge 3.2' de verilmiştir.

Çizelge 3.2 İncelenen özelliklere ait ortalama değerler ve oluşan gruplamalar

Uygulama	Kısa Lif Oranı (Adet)	Olgunluk (g)	Nem (g)	Parlaklık (Adet)	Sarılık (Adet)
1. Kontrol	7,35	0,89	7,52	74,37	10,20
2. Zn (45)	7,57	0,90	7,45	74,65	10,00
3. Zn (45 + 60)	7,47	0,89	7,45	73,67	10,20
4. Zn (45 + 60 +75)	7,87	0,89	7,57	75,17	10,20
5. Bor (45)	7,05	0,89	7,37	74,47	10,12
6. Bor (45 + 60)	7,65	0,90	7,35	74,60	10,02
7. Bor (45 + 60 +75)	7,62	0,90	7,47	72,50	10,02
Ortalama	7,51	0,89	7,45	74,20	10,11
CV (%)	17,75	0,77	3,81	1,82	3,19
LSD (0.05)	ÖD	ÖD	ÖD	ÖD	ÖD

*** ; % 1 seviyesinde, * ; % 5 seviyesinde önemlidir.*

Kısa lif oranı SFI (%): Çizelge 3.2'den kısa lif indeksi yönüyle değerlerin uygulamalara göre değişmek üzere %7,05 ile %7,87 arasında değişim gösterdiği izlenebilmektedir. Uygulamalar arasında istatistiksel önem düzeyinde bir farklılığın olmadığı izlenebilmektedir. En düşük değer %7,05 ile 5 numaralı uygulamadan elde edilmiştir. En yüksek değer ise % 7,87 ile 4 numaralı uygulamadan elde edilmiştir. Denemenin genel ortalamasının % 7,51 olduğu görülmektedir. Bu çalışmanın sonucu önceki çalışmalardan Tekin (2011)'in elde ettiği sonuçlar ile benzerlik göstermektedir.

Lif olgunluk indeksi : Çizelge 3.2'den Olgunluk değerleri yönüyle elde edilen bulgular uygulamalara göre değişmek üzere % 89 ile %90 arasında değişim göstermiştir, ancak uygulamalar arasında istatistiksel önem seviyesinde bir değişikliğin olmadığı gözlenmiştir.

Nem (%) : Çizelge 3.2'den Nem değerleri yönüyle elde edilen sonuçlar uygulamalara göre değişmek üzere % 7,35 ile 7,57 arasında değişim göstermiştir, ancak uygulamalar arasında önemli bir farklılık elde edilmemiştir. Denemenin genel ortalamasının %7,45 olduğu görülmektedir.

Parlaklık (Rd) : Çizelge 3.2'den Parlaklık değerleri yönüyle elde edilen sonuçların uygulamalara göre değişmek üzere 72,50 ile 75,17 arasında değişim gösterdiği, ancak uygulamalar arasında istatistiksel olarak bir faklılığın oluşmadığı belirlenmiştir. Araştırmanın genel ortalamasının 74,20 olduğu izlenebilmektedir.

Sarılık (+b) : Çizelge 3.2'den Sarılık değerleri yönünden elde edilen sonuçlar uygulamalara göre değişmek üzere % 10,00 ile 10,20 arasında değişim göstermiştir, yapılan istatistiksel analiz sonuçları yapılan uygulamaların bu özellik üzerine etkili olmadığını göstermiştir.

4. Sonuç

Yürütülen bu çalışmada ekimden 45 (taraklanma dönemi), 60 (çiçeklenme dönemi) ve 75 (çiçeklenme doruğu) gün sonra yapraktan çinko ve bor bitki besin elementleri uygulanmıştır. Taraklanma, çiçeklenme ve çiçeklenme doruğunda gerçekleştirilen çinko uygulamasının incelenen lif kalite özellikleri üzerine bir etkisinin olmadığı ortaya konulmuştur. Literatür araştırmalarında pamukta çinko uygulamasının hem önemli etsinin olduğuna hem de önemsiz olduğuna ilişkin sonuçlar bulunmaktadır. Bu nedenle çalışmanın en az bir yıl daha yürütülerek bu konuda bir öneride bulunmak daha sağlıklı olabilir.

Bor uygulamalarının sonuçları değerlendirildiğinde, ekimden sonra 45, 60 ve 75'inci günlerde yapılan lif kalite özellikleri üzerine bir etkisinin olmadığı ortaya konulmuştur. Önceki çalışmalarda pamukta bor uygulamasının hem önemli etsinin olduğuna hem de önemsiz olduğuna ilişkin sonuçlar bulunmaktadır. Bu nedenle çalışmanın en az bir yıl daha yürütülerek bu konuda bir öneride bulunmak daha sağlıklı olabilir.

İncelenen tüm lif kalite özellikleri bakımından uygulamalar arasında önemli bir farklılık elde edilmemiştir, bu sonuçlar çinko ve bor uygulamasının lif kalitesinde herhangi bir farklılığa neden olmadığını ortaya koymuştur, ancak bu çalışmadan elde edilen sonuçlar önceki çalışmalarda elde edilen ve çinko ve bor'un lif kalite özelliklerinde önemli farklılıklar elde edildiğine ilişkin sonuçlar ile örtüşmemektedir. Bu sonuçlar denemenin yürütüldüğü çevre şartları ve kullanılan materyalden kaynaklanmış olabilir. Ancak çalışmanın en az bir yıl daha yürütülmesi daha net öneri yapılması bakımından önemlidir.

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DETERMINATION OF THE ANTAGONISTIC EFFECTS OF PLANT GROWTH-PROMOTING RHIZOBACTERIA AGAINST *Rhizoctonia solani* CAUSED PEPPER ROOT ROT

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ABSTRACT

This study aimed to determine the antagonistic effects of different plant growth-promoting rhizobacteria (PGPR) against *Rhizoctonia solani*. In the study, 20 PGPR isolates obtained from soil samples collected from pepper, wheat, and chickpea production areas, as well as forest areas in the provinces of Çorum, Tokat, and Yozgat, were used. In addition, a *Rhizoctonia solani* fungal pathogen isolate was obtained from the root regions of diseased pepper plants collected during field surveys conducted in pepper production areas of Tokat province. The study was carried out as an in vitro Petri assay using a dual culture test. PGPR isolates were cultured on Nutrient Agar (NA), while *R. solani* was grown on Potato Dextrose Agar (PDA). Antagonistic activity was evaluated on Tryptic Soy Agar (TSA). Bacterial isolates were inoculated in a circular pattern onto the prepared medium and incubated at 25±2 °C for 24 hours. At the end of this period, a 5 mm diameter mycelial disc of *R. solani* was placed at the center of the medium. Petri dishes were sealed with parafilm and incubated at 25±2 °C for 7 days. In the control group, only the pathogen disc was used without bacterial inoculation. Five Petri dishes were used for each bacterial isolate, and the experiment was repeated once. At the end of the incubation period, the experiment was terminated when the pathogen completely covered the Petri dishes in the control group. The mycelial diameters of the pathogen in both control and treatment groups were measured using a caliper, and the inhibition rates of bacterial isolates on *R. solani* mycelial growth were calculated. According to the results of the dual culture tests, the 20 tested PGPR isolates exhibited inhibitory effects against *R. solani* ranging from 29.48% to 87.72%. The highest inhibition rate (87.72%) was recorded in isolate YO10-c, followed by isolate TOT1-a (*Pseudomonas corrugata*) with an inhibition rate of 63.23%. In addition, isolate YO-2-e (*Pseudomonas putida*) showed a moderate antagonistic effect with an inhibition rate of 50.53%. The remaining isolates exhibited inhibition rates of 29.48% and 45.69% indicating a limited suppression of pathogen growth. The results of this study demonstrated that local bacterial isolates are effective against the root rot pathogen *R. solani* in pepper under

in vitro conditions. However, further greenhouse and field studies are required to evaluate their effectiveness under in vivo conditions.

Keywords: Plant Growth-Promoting Rhizobacteria, *Rhizoctonia solani*, Pepper, *in vitro*

BİBER KÖK ÇÜRÜKLÜĞÜ ETMENİ *Rhizoctonia solani*'YE KARŞI BİTKİ BÜYÜMESİNİ TEŞVİK EDEN RİZOBAKTERİLERİN ANTAGONİSTİK ETKİLERİNİN BELİRLENMESİ

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ÖZET

Bu çalışmada, farklı bitki büyümesini teşvik eden rizobakterilerin (PGPR) *Rhizoctonia solani*'ye karşı antagonistik etkilerinin belirlenmesi amaçlanmıştır. Çalışmada Çorum, Tokat ve Yozgat illerinde biber, buğday ve nohut üretim alanlarından ve ormanlık alanlardan alınan toprak örneklerinden izole edilen 20 adet PGPR ve Tokat ili biber üretim alanlarında yapılan arazi incelemelerinde hastalıklı biber bitkilerinin kök bölgelerinden izole edilen *Rhizoctonia solani* patojen fungus izolatı kullanılmıştır. *In vitro*-petri denemesi şeklinde yürütülen çalışmada ikili kültür testi yapılmıştır. PGPR'lar Nutrient Agar (NA), *R. solani* Patates Dekstroz Agar (PDA) besi yerinde geliştirilmiştir. Antagonistik etki ise Triptik Soy Agar (TSA) besi yerinde gerçekleştirilmiştir. Hazırlanan besi yerine bakteri izolatları halka şeklinde inoküle edilmiş ve 25±2 °C'de 24 saat inkübe edilmiştir. Bu sürenin bitiminde besi yerinin merkezine 5 mm çapında *R. solani* miselyum diski yerleştirilmiştir. Petri kapları parafilm ile kapatılarak 25±2 °C'de 7 gün süreyle inkübasyona bırakılmıştır. Kontrol grubunda ise bakteri inokulasyonu yapılmaksızın yalnızca patojen diski kullanılmıştır. Her bir bakteri izolatı için beş petri kullanılmış ve deneme bir kez daha tekrarlanmıştır. İnkübasyon süresi sonunda, kontrol petrilerinde patojenin petriyi tamamen kaplaması esas alınarak deneme sonlandırılmıştır. Kontrol ve uygulama gruplarında patojenin miselyum çapları kumpas yardımıyla ölçülmüş ve bakterilerin *R. solani* miselyum gelişimini engelleme oranları hesaplanmıştır. İkili kültür testleri sonucunda, testlenen 20 PGPR izolatının *R. solani* üzerinde %29,48-87.72 arasında değişen oranlarda etkili olduğu belirlenmiştir. En yüksek engelleme oranı %87,72 ile YO10-c izolatında belirlenmiş olup, YO10-c izolatını %63,23 engelleme oranı ile TOT1-a izolatı (*Pseudomonas corrugata*) takip etmiştir. Ayrıca, %50,53 engelleme oranı ile YO-2-e izolatı (*Pseudomonas putida*) orta düzeyde antagonistik etki göstermiştir. Diğer izolatlar

ise sırasıyla %29,48 ve %45,69 ve oranlarında engelleme göstererek patojen gelişimini sınırlı düzeyde baskılamıştır.Yürütülen bu çalışma ile yerel bakteri izolatlarının, biber bitkisinde kök çürüklük etmeni *R. solani*'ye *in vitro* koşullarda etkili olduğu ortaya konulmuş olup buna ilaveten sera ve arazi çalışmaları ile biber bitkisinde hastalığa olan etkinin belirlenmesi gerekmektedir.

Anahtar Kelime: Bitki Büyümesini Teşvik Eden Rizobakteri, *Rhizoctonia solani*, Biber, *in vitro*

1. Introduction

Pepper (*Capsicum annuum* L.) is an important vegetable species widely cultivated worldwide due to its rich nutritional content and diverse uses. The high levels of ascorbic acid (vitamin C), carotenoids, and phenolic compounds in its fruits contribute to its strong antioxidant properties (Howard et al., 2000; Materska & Perucka, 2005; Wahyuni et al., 2011). Pepper is not only a basic food source but also an important agricultural product considered a functional food due to its health-promoting effects. Besides fresh consumption, it is also used in dried form, as paste, pickles, and as a spice.

Worldwide pepper production has shown a consistent upward trend over the last twenty years. According to FAO (2024) data, world pepper production is approximately 38 million tons, with China, India, and Mexico being among the leading countries. Turkey, thanks to its favorable climatic conditions, has a significant share in world pepper production with approximately 3,4 million tons. According to TÜİK (2025) data, peppers hold an important place in vegetable production in Turkey and are cultivated intensively, especially in the Mediterranean and Aegean regions.

One of the most important factors limiting yield and quality in pepper cultivation is disease agents belonging to different pathogen groups. Soil-borne fungal pathogens, in particular, are more destructive than other disease agents due to their long-term viability and wide host range (Agrios, 2005). In this context, pathogens such as *Phytophthora capsici* L., *Rhizoctonia solani*, *Fusarium oxysporum*, and *Verticillium dahliae* are among the main factors causing significant yield and quality losses in pepper production (Lamour et al., 2012; Sasirekha and Srividya, 2016; Coşkun et al., 2021; Güneş, 2026).

The primary reason for the destructive nature of soil-borne fungal diseases is the ability of pathogens to survive for extended periods in the soil by forming resistant structures. *R. solani* forms sclerotia-like structures, while *V. dahliae* forms microsclerotia, remaining viable in the soil for years (Keijer, 1996; Geng et al., 2022). These resistant structures allow pathogens to exhibit resistance to adverse environmental conditions and chemical control interventions (Fan et al., 2017). Furthermore, their wide host range and the accumulation of inoculum in the soil further limit the control of these pathogens (Shafique et al., 2016; Panth et al., 2020). While bacterial and viral disease agents are also important, their spread is largely dependent on environmental

conditions, and their persistence in the soil remains more limited compared to fungal pathogens (Jones et al., 2004; Kenyon et al., 2014).

Among these pathogens, *R. solani* is one of the prominent factors causing significant economic losses in pepper cultivation. Studies conducted by various researchers in our country have shown that this pathogen is widespread in pepper production areas and causes serious losses, especially in the early development stages (Tenis & Demirer Durak, 2023; Yıldırım, 2017; Boyraz & Karaca, 1991). The pathogen particularly causes damping-off disease in the seedling stage, reducing emergence rates, and negatively affects plant development by causing root and crown rot (Ajayi-Oyetunde & Bradley, 2018). The pathogen's wide host range and its ability to remain viable in the soil for a long time are among the primary factors that increase the persistence of the disease (Carling et al., 2002).

While chemical methods are generally used in the fight against disease agents, the environmental side effects and sustainability risks posed by these practices highlight the need for developing alternative strategies. In this context, biological control approaches are gaining increasing importance, and plant growth-promoting rhizobacteria (PGPRs) are proving to be an effective option. PGPRs can suppress pathogen development through various means, such as antibiotic production, creating competition for nutrients, and activating induced systemic resistance mechanisms in plants (Egamberdieva et al., 2023; Rana et al., 2025).

Numerous studies have demonstrated that bacteria isolated from the rhizosphere exhibit effective antagonistic properties against soil-borne fungal pathogens. These studies include those aimed at suppressing *R. solani*. In this context, Anak et al. (2021) tested 83 bacterial isolates obtained from volcanic, sandy, and saline soils, as well as from the *Calligonum polygonoides* L. subsp. Comosum plant, against *R. solani,* which causes root rot in beans, and found 20 isolates to be effective in *in vitro* tests. They stated that the inhibition rates of the disease agent varied between 50-66% among the bacteria. In a study by Akbaba and Genç (2024), the biocontrol properties of 10 different rhizobacteria isolated from the tomato rhizosphere against *F. oxysporum* HMK2-6, *R. solani* HB-66, and *V. dahliae* YY-14 pathogens in tomato plants were evaluated. *In vitro* tests revealed that the *Pseudomonas chlororaphis* T142 strain showed a biocontrol effect of 19.9%, and the *Bacillus subtilis* T139 strain showed a biocontrol effect of 11.9%.

Based on this information, the aim of this study is to determine the antagonistic effects of plant growth-promoting rhizobacteria (PGPR) isolated from different soils on *R. solani* under *in vitro* conditions.

2.Materials And Methods

Pathogens Used in the Study

In this study, the *Rhizoctonia solani* pathogen, isolated from pepper plants and maintained in the stock culture of the Phytopathology Laboratory of the Department of Plant Protection, Faculty of Agriculture, Tokat Gaziosmanpaşa University, was used.

PGPR Used in the Study

In this study, 20 plant growth-promoting rhizobacteria (PGPR) isolates, isolated from different soil samples taken from Çorum, Tokat and Yozgat provinces and preserved in the stock culture collection of the Phytopathology Laboratory, Department of Plant Protection, Faculty of Agriculture, Tokat Gaziosmanpaşa University, were used (Table 1).

Table 1. PGPR bacteria used in the study and their characteristics

Bacteria Code	Bacteria name	37° C test	Potato Pectolytic Activity Test	HR test in tobacco	KOH Test	Nitrogen Binding Test	Phosphorus Dissolution Test
YO10-c		-	-	-	-	+	+(4.35)
MBB-6	*Pseudomonas corrugata*	-	-	-	+	+	+(8.47)
YO2-e	*Pseudomonas putida*	-	-	-	+	+	-
O-5-b		-	-	-	+	+	+(3.47)
MBB-1	*Bacillus arcenicus*	-	-	-	-	+	-
MBB-3		-	-	-	+	+	-
MBB-11	*Bacillus cereus*	-	-	-	-	+	-
MBB-7	*Pseudomonas brassicacearum*	-	-	-	-	+	+(6.34)
MBB-5	*Pseudomonas* sp.	-	-	-	-	+	+(8.47)
MBB-12	*Pseudomonas mandelii*	-	-	-	-	+	+(5.87)
YO10-a1		-	-	-	-	+	+(2.65)
MBB-10	*Pantoea agglomerans*	-	-	-	-	+	+(6.12)
MBB-4		-	-	-	-	+	+(6.18)
MBB-8		-	-	-	-	+	+(2.79)
MSD-5	*Pseudomonas corrugata*	-	-	-	+	+	+(3.97)
MBB-2	*Pseudomonas thivervalensis*	-	-	-	-	+	+(9.55)
TOT-2-m		-	-	-	+	+	+(3.54)
MBB-9	*Pseudomonas cedrina* spp. *cedrina*	-	-	-	-	+	+(4.91)
YO4-a		-	-	-	+	+	+(4.25)

TOT-6-a		-	-	-	-	+	+(4.11)

Isolation of *Rhizoctonia solani* from pepper

As part of field studies conducted in different districts of Tokat province, samples were collected from pepper (*Capsicum annuum* L.) plants showing disease symptoms. Small pieces taken from infected plant tissues were immersed in 70% ethanol for 1–2 minutes for surface sterilization and washed twice with sterile distilled water. Following the washing process, the tissue pieces were dried briefly in a sterile environment. The dried samples were placed on Potato Dextrose Agar (PDA) medium, with the infected parts in contact with the medium, for pathogen isolation and incubated at 25±2 °C for 5–7 days (Soylu et al., 2021). Pure fungi cultures obtained from mycelium growing in the culture medium were sent to the Plant Health Clinic Application and Research Center of Hatay Mustafa Kemal University for identification, and their identification was performed using a MALDI-TOF MS (Bruker Daltonics GmbH, Germany) device (Soylu et al., 2022).

Dual Culture Test

In previous studies using dual culture tests, a total of 20 bacterial isolates from different sources were evaluated for antagonistic effects against *R. solani*. The bacterial isolates used in this study were cultured on Nutrient Agar (NA) medium, while the pathogenic fungus was grown on Potato Dextrose Agar (PDA) medium. To more clearly observe the antagonistic interaction, the tests were performed on Tryptic Soy Agar (TSA) medium. Bacteria were inoculated in a ring shape onto sterile media and incubated at 25±2 °C for 24 hours. After this time, a 5 mm diameter *R. solani* mycelium disc was placed in the center of the medium (Figure 1) and incubated at 25±2 °C for 7 days. As a control, only the pathogenic disc was placed in petri dishes without bacterial marking. Three petri dishes were used for each bacterial isolate, and the experiment was repeated once more. The experiment was terminated when fungal mycelium growth covered the control petri dish (90 mm in diameter) at the end of the incubation period. The diameters of the pathogenic fungus mycelium in both the control and bacterially treated petri dishes were measured using a caliper. The rate at which the bacteria inhibited *R. solani* mycelium growth was calculated (Ezziyyani et al., 2004).



Figure 1. Placement of *R. solani* disc in TSA medium

Statistical Analysis

IBM SPSS Statistics 26 software package was used to evaluate the data obtained at the end of the experiment. A one-way analysis of variance (ANOVA) test was performed to determine whether there were differences between the applications in terms of the examined characteristics, and the Duncan test, a multiple comparison test, was used based on the results of the ANOVA test.

3. Results

In dual culture tests, the antagonistic effects of 20 bacterial isolates isolated from soil samples on *R. solani* were evaluated. The tests revealed that the bacteria inhibited the pathogen's mycelial growth by rates ranging from 29.48% to 87.72% (Table 2, Figure 2).

Table 2. Inhibition rates of R. solani by the bacteria used in the study

Code	**Bacterial Name**	**Blocking Rate (%)**
YO10-c		87.72±1.57 f*
MBB-6	*Pseudomonas corrugata*	63.23±18.76 e
YO-2-e	*Pseudomonas putida*	50.53±14.01 de
O-5-b		45.69±4.92 cd
MBB-1	*Bacillus arcenicus*	44.86±4.52 bcd

MBB-3		44.82±2.00[bcd]
MBB-11	*Bacillus cereus*	42.65±7.74[abcd]
MBB-7	*Pseudomonas brassicacearum*	41.26±7.05[abcd]
MBB-5	*Pseudomonas* sp.	40.92±4.74[abcd]
MBB-12	*Pseudomonas mandelii*	40.77±4.19[abcd]
YO10-a1		40.74±6.37[abcd]
MBB-10	*Pantoea agglomerans*	40.12±6.85[abcd]
MBB-4		39.48±2.24[abcd]
MBB-8		39.05±6.61[abcd]
MSD-5	*Pseudomonas corrugata*	38.87±5.64[abcd]
MBB-2	*Pseudomonas thivervalensis*	35.03±1.94[abc]
TOT-2-m		34.96±3.50[abc]
MBB-9	*Pseudomonas cedrina* spp. *cedrina*	33.44±3.28[abc]
YO4-a		30.33±4.89[ab]
TOT-6-a		29.48±3.59[a]

*Means indicated with the same letters in a column are not significantly different

According to the results of the dual culture test, the inhibition rates of bacterial isolates isolated from different soil samples on *R. solani* were determined to range from 29.48% to 87.72% (Figure 2). The highest inhibition rate was observed in isolate YO10-c with 87.72%, and this isolate was found to be statistically significantly more effective than all other isolates. YO10-c was followed by MBB-6 (*Pseudomonas corrugata*) with 63.23% and YO-2-e (*P. putida*) with 50.53%, but the effect of these isolates was significantly lower than the highest value.

Similar studies in the literature also report that the antagonistic effect among bacterial isolates varies widely. In their study, Abou-Aly et al. (2015) showed that 19 out of 116 bacterial isolates exhibited the highest inhibition percentage against *F. oxysporum, R. solani*, and *S. rolfsii,* and stated that the effect of different rhizobacteria on *R. solani* ranged from 2.2% to 77.4%. However, it has also been reported in the literature that *Bacillus* and *Pseudomonas* species can achieve higher suppression rates. In a study conducted on lawns, it was reported that some *Bacillus* and *Pseudomonas* isolates showed disease suppression effects against *R. solani* ranging from 81.59% to 91.43% (Şenocak et al., 2020). In a study conducted by Mraben et al. (2013) on black wart disease caused by *R. solani* in potatoes, it was reported that *Pseudomonas* species suppressed pathogenic mycelial development by approximately 50% and reduced disease severity. Similarly, it was determined that *Pseudomonas fluorescens* isolates applied against seedling root rot disease caused by *R. solani* in tobacco significantly reduced disease symptoms and increased plant growth

(Vallabhaneni, 2016). In this study conducted by us, the antagonistic effect of *Pseudomonas corrugata* (63.23%) and *P. putida* (50.53%) isolates against *R. solani* was found to be consistent with the literature.

In pathogen-PGPR interactions, the effect of bacterial isolates on the pathogen can vary depending on the genus, species, density of the bacteria, and the culture medium used. Indeed, a study by Toppo and Tiwari (2015) reported that different *Pseudomonas* isolates significantly suppressed the mycelial growth of *R. solani*, but the effectiveness varied among the isolates, with some showing only moderate inhibition. Similarly, a study examining the antagonistic properties of soil-borne *Pseudomonas* populations indicated that these bacteria exhibited antifungal effects, but this effect varied among the isolates, and not all isolates produced high levels of suppression (Garbeva et al., 2004). Similarly, in the present study, it was determined that isolates MBB-11 (*B. cereus*), MBB-7 (*P. brassicacearum*), MBB-5 (*Pseudomonas* sp.), MBB-12 (*P. mandelii*), YO10-a1, MBB-10 (*Pantoea agglomerans*), MBB-4, MBB-8, and MSD-5 (*P. corrugata*) suppressed *R. solani* growth at rates ranging from 38.87% to 42.65%, and no statistically significant difference was found among these isolates. Isolates MBB-2 (*P. thivervalensis*) (35.03%), TOT-2-m (34.96%), and MBB-9 (*P. cedrina* spp. *cedrina*) (33.44%) showed similar values, placing them in the same statistical group and demonstrating a lower effect compared to the previous group. The lowest inhibition rates were observed in isolates YO4-a (30.33%) and TOT-6-a (29.48%), demonstrating significantly weaker antagonistic effects compared to others. Overall, this study reveals that antagonistic effects show significant differences at the isolate level rather than the species level, highlighting the critical importance of selecting effective strains in biological control. Statistically significant differences were found among the isolates in this study, with isolate YO10-c showing particularly high inhibition.

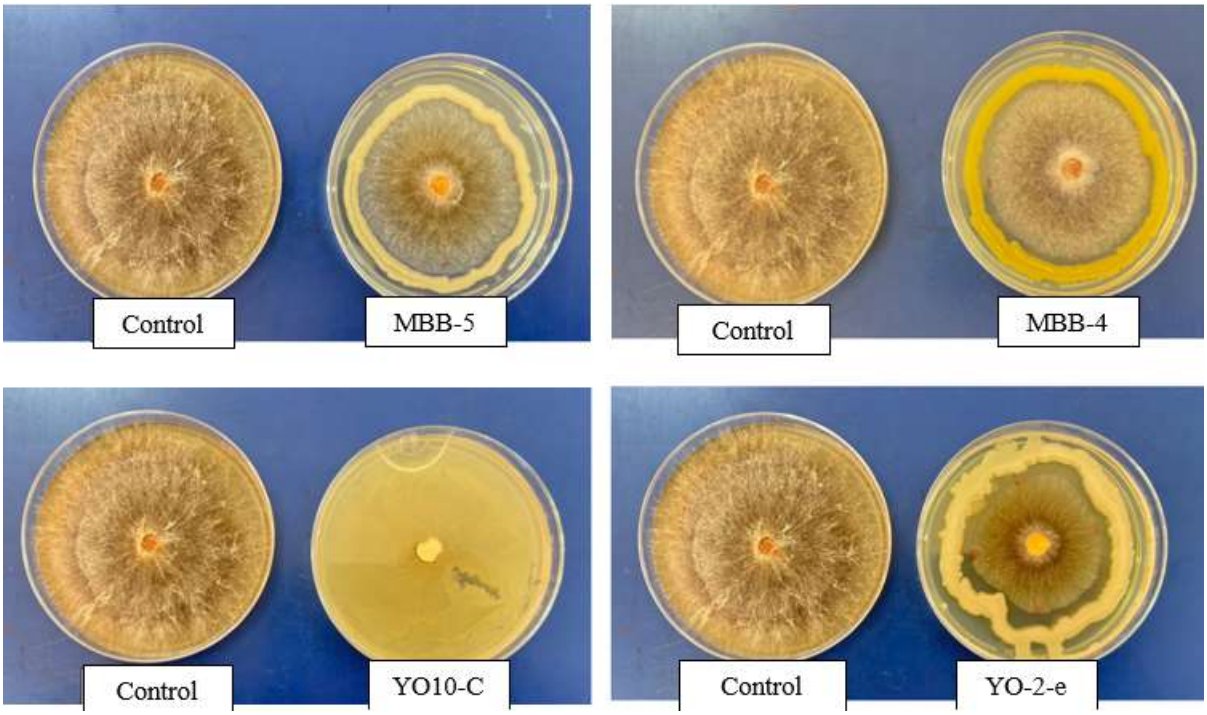


Figure 2. Pathogen-PGPR interaction (double culture test results)

4.Conclusion

This study evaluated the in vitro antagonistic effects of local bacterial isolates, isolated from soil, against *Rhizoctonia solani,* a pathogen causing root rot in pepper plants. The findings revealed that some bacterial isolates were able to significantly suppress the mycelial growth of the pathogen. This indicates that these isolates have potential for biological control. In conclusion, it is thought that the identified effective local bacterial isolates can be evaluated as biological agents that can reduce the use of chemical fungicides in the control of plant diseases and provide an environmentally friendly alternative.

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A CASE OF OBSTRUCTIVE DYSTOCIA CAUSED BY TRANSMISSIBLE VENEREAL TUMOR (TVT) IN A BITCH

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ABSTRACT

In this case report, the diagnostic and treatment process of obstructive dystocia, urinary obstruction, and intrauterine fetal death developing secondary to transmissible venereal tumor (TVT) in a pregnant bitch was presented. A five-year-old, 18-kg, mixed-breed stray bitch was brought to the Clinic of the Department of Obstetrics and Gynecology, Animal Hospital, Faculty of Veterinary Medicine, Hatay Mustafa Kemal University, with the complaints of vaginal bleeding, inability to urinate, and deterioration of general condition. On clinical and gynecological examination, a hemorrhagic, fragile mass originating from the ventral floor of the vagina and completely occluding the vaginal inlet, including the external urethral orifice, was detected. In line with the preliminary diagnosis of TVT, vaginal smear samples were collected, stained with Giemsa,

and cytological examination revealed a neoplastic cell population compatible with TVT, containing typical intracytoplasmic vacuoles. Upon detection of green-colored and foul-smelling discharge during vaginal examination, abdominal ultrasonographic examination was performed to evaluate possible uterine and fetal pathologies. Ultrasonographic examination revealed that the dog was pregnant; however, no fetal heartbeats were present, and all fetuses had died intrauterinely. In addition, marked dilatation of the urinary bladder was observed. Serum biochemical analyses showed increased urea (92 mg/dL) and creatinine (3.4 mg/dL) levels consistent with post-renal azotemia, while complete blood count revealed moderate leukocytosis ($23.68\times10^3/\mu L$) and neutrophilia (88.1%). After stabilization of the patient's vital parameters, ovariohysterectomy was performed and the intrauterine dead fetuses were removed together with the uterus. The vaginal mass causing urinary retention was also resected during the same operation. In the postoperative period, a broad-spectrum combined antibiotic, nonsteroidal anti-inflammatory, and supportive treatment protocol was maintained for 7 days. Vincristine treatment was initiated after suture removal on postoperative day 14, and complete clinical recovery was achieved during the follow-up period. This case demonstrates that TVT may become a serious obstetric-oncologic emergency during pregnancy by causing obstruction of the birth canal and fetal losses.

Keywords: bitch, pregnancy, transmissible venereal tumor, obstructive dystocia, ovariohysterectomy.

1. Introductıon

Transmissible Venereal Tumour (TVT), known as the infectious tumour of dogs, is a round-cell neoplasm commonly observed among genital tumours and exhibits infectious properties (Murgia et al. 2006). To date, research on mammals has identified three distinct types of infectious tumours: canine transmissible venereal tumour, Tasmanian Devil Facial Tumour Disease (DFTD), and a tumour with similar characteristics identified in Syrian hamsters (Ayala et al. 2018). It has been reported that TVT cases account for 63% of vaginal tumours observed in dogs (Çızmecı and Guler 2018). In a five-year retrospective study, TVT was identified in 123 out of 1,522 dogs (8.08%) (Araujo et al. 2016). It can be observed in adult dogs aged 9–13 months on average (Salt et al. 2005, Morris and Dobson 2001), and the majority of cases involve animals weighing over 18–20 kg (Nak 2001). While dog somatic cells contain 78 chromosomes, TVT cells contain 59 chromosomes (Ortega-Pacheco et al. 2003). Additionally, it has been reported that the cells undergo genetic variations shortly after the tumour's emergence and have spread within the canine population with limited genetic variation to the present day (Ayala-Díaz et al. 2017).

TVT typically occurs when live tumour cells pass through mucosa with compromised integrity during mating. It can also be transmitted through licking, biting, and sniffing of tumourous areas (Das and Das 2000). Haemorrhagic discharge, neoplastic lesions, and foul odour in the genital organs are common clinical findings (Kose et al. 2013).

The development of tumour cells following implantation in the reproductive system spans approximately 2–6 months and is characterised by exponential growth (Ayala-Díaz et al. 2017). In female dogs, TVT is most commonly localised in the vestibule and vaginal region (Ganguly et al. 2013). It has also been reported in various body regions, including the oral cavity, nasal cavities, ocular structures, and skin (Herrera et al. 2006, Rebbeck et al. 2009, Ojeda et al. 2016). Lesions can occur regardless of sex or breed, and in most cases, they are limited to the mucous membranes of the external genital organs (Amaral et al. 2004). Although there is no clear breed predisposition to the disease, Terrier breeds may be more susceptible (Gonzalez et al. 2000). The incidence of the disease is higher in female dogs than in males, and this contributes to the increased spread of the disease as carrier male dogs mate with a large number of females (Das and Das 2000). It has also been reported that the disease occurs at lower rates in purebred dogs (Herrera et al. 2006, Ramírez Romero et al. 2012). While prevalence varies globally, stray dogs play a significant role in the spread of the disease (Ortega-Pacheco et al. 2003). The disease is reported to be prevalent in areas with dense dog populations where reproductive control is inadequate (Ganguly et al. 2016). In endemic regions, animals under one year of age have been reported to be at risk (Çızmecı and Guler 2018).

2. Clinical Findings and Diagnosis

The case involved a 4-year-old stray dog brought to the Obstetrics and Gynaecology Clinic at the Faculty of Veterinary Medicine, Hatay Mustafa Kemal University. The medical history

revealed a loss of appetite that had persisted for several days, along with marked abdominal distension and a bloody vaginal discharge that had been present for approximately 14 days.

During the clinical examination, in addition to the findings from the history, a bleeding mass located ventrally within the vulva was observed **(Figure 1AB).**

The typical appearance of the mass in the vagina, which was bleeding and easily fragmentable, suggested the possibility of TVT. An ultrasonographic examination was performed to determine the cause of the abdominal distension. The abdominal ultrasound revealed that the animal was pregnant but had no detectable fetal heartbeat. Significant dilation of the urinary bladder was also observed.

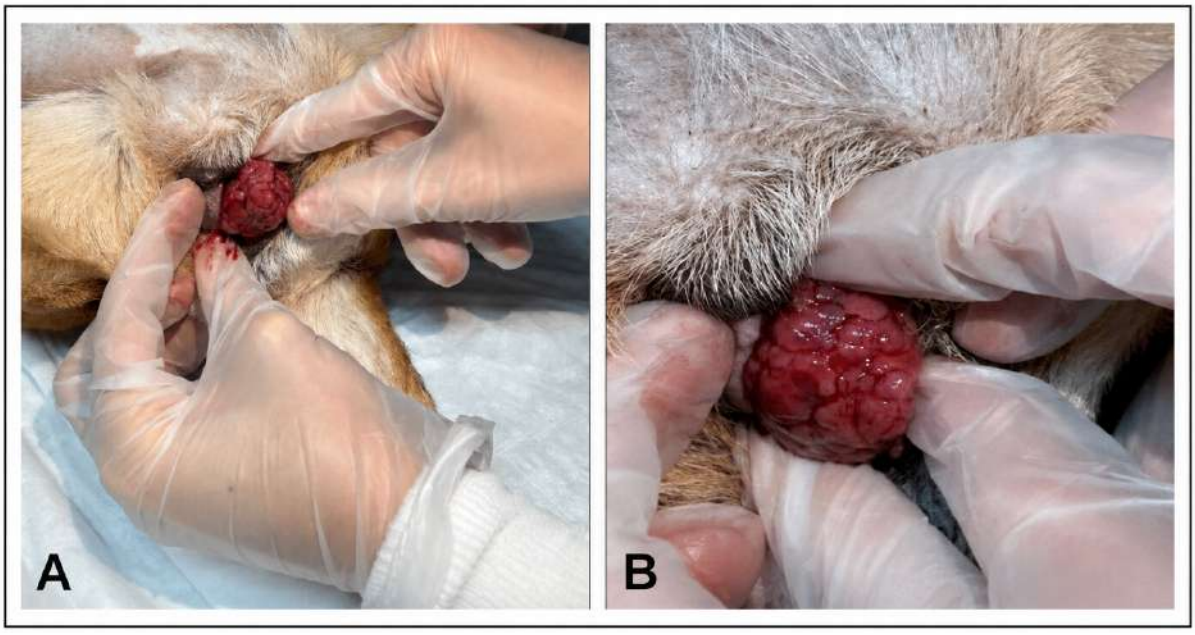


Figure 1. (A). Macroscopic appearance of the mass within the vulva. **(B).** Close-up view of the mass.

In accordance with the preliminary diagnosis of TVT, the slides prepared from vaginal cytology samples were stained using the May-Grünwald-Giemsa protocol. **(Figure 2.)**

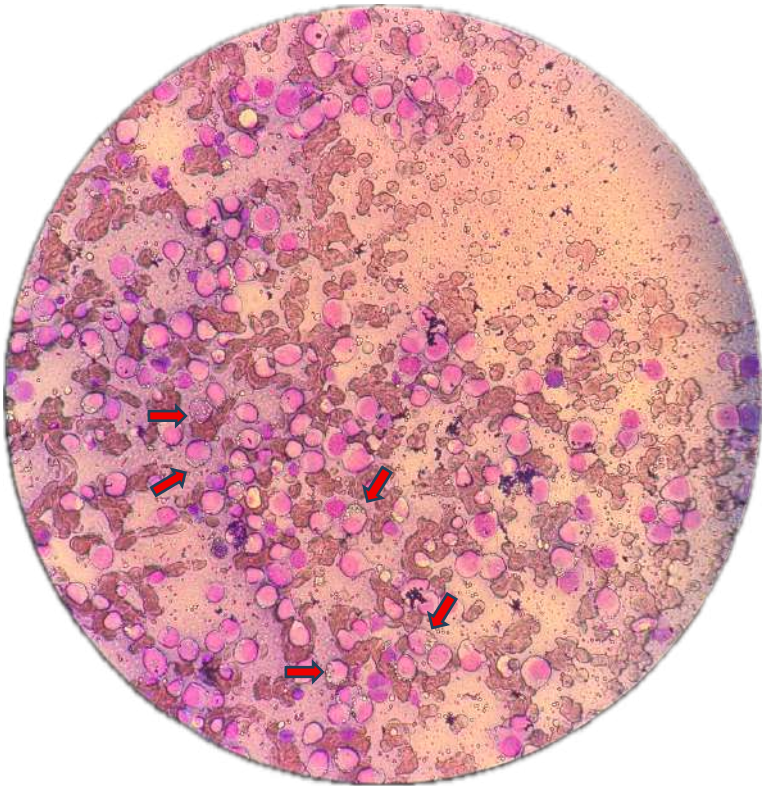


Figure 2. Intracellular cells containing vacuoles (red arrow).

Due to the patient's poor general condition and suspected fetal death, an emergency caesarean section was performed. Before the procedure, the patient underwent a complete blood count and serum biochemistry tests to assess her overall health. The haematological examination showed moderate leukocytosis (23.68 × 10^3/µL) and neutrophilia (88.1%) in the complete blood count. **(Figure 3).**

PARAMETER	RESULT	REFERENCE INTERVAL	UNİT
WBC	23.68	6.0–17.0	×10^3/µL
LYM (%)	21.3	12.0–30.0	%
MON (%)	3.8	2.0–10.0	%
NEU (%)	68.1	60.0–83.0	%
EOS (%)	6.3	2.0–10.0	%
BAS (%)	0.5	—	%
RBC	5.71	5.5–8.5	×10^6/µL
HGB	11.8	12.0–18.0	g/dL
HCT	37.3	38.0–55.0	%
MCV	65.4	60–77	fL

MCH	20.9	19.5–24.5	pg
MCHC	30.5	30–36	g/dL
RDW	14.8	12.0–17.0	%
PLT	465	120–600	$\times 10^3/\mu L$
MPV	9.1	5.0–12.0	fL
PCT	0.42	—	%
PDW	7.8	6.0–10.0	fL

Figure 3. Haematological findings.

Xylazine HCl (Sanalazin 20, 50 ml, Santavet, Turkey) was administered at a dose of 1–2 mg/kg for premedication. Ketamine HCl (Keta-Control, 25 ml, Doğa İlaç, Turkey) was used at a dose of 10–20 mg/kg for induction. Once adequate anaesthetic depth was achieved, the patient was intubated and maintained under inhalation anaesthesia with Isoflurane (Isoflurane USP 100% Inhalation Solution, 100 ml, Adeka İlaç, Turkey). Respiratory and cardiovascular parameters were monitored throughout the procedure. The patient was positioned in ventro-dorsal recumbency on the operating table. As part of routine surgical preparation, the abdominal area was shaved to ensure asepsis and antisepsis. A 5-cm skin incision was made along the midline, approximately 2 cm caudal to the umbilicus. The subcutaneous tissue and muscle layers were dissected to reach the linea alba. The linea alba was incised to enter the abdominal cavity and access the uterus. An incision was made in the greater curvature of the uterus to remove the fetuses using a milking motion. However, it was found that the fetal membranes were adherent to the uterine wall, and the fetuses could not be advanced. As the fetuses could not be removed after the initial incision, the incision was extended, and the first pup was extracted. Multiple incisions were made in different regions of the uterus to remove the remaining pups. A total of eight pups were extracted, all of which were found to be dead **(Figure 4).**



Figure 4. Postoperative puppies.

During the removal of the fetuses, changes in the colour of the fetal membranes (brownish-greenish discolouration), severe degenerative changes, disruption of tissue integrity, increased fragility, and signs of autolysis in some areas were observed. In addition, the amniotic fluid appeared cloudy and malodorous. These findings were interpreted as consistent with intrauterine fetal death and postmortem autolytic changes **(Figure 5. AB).**

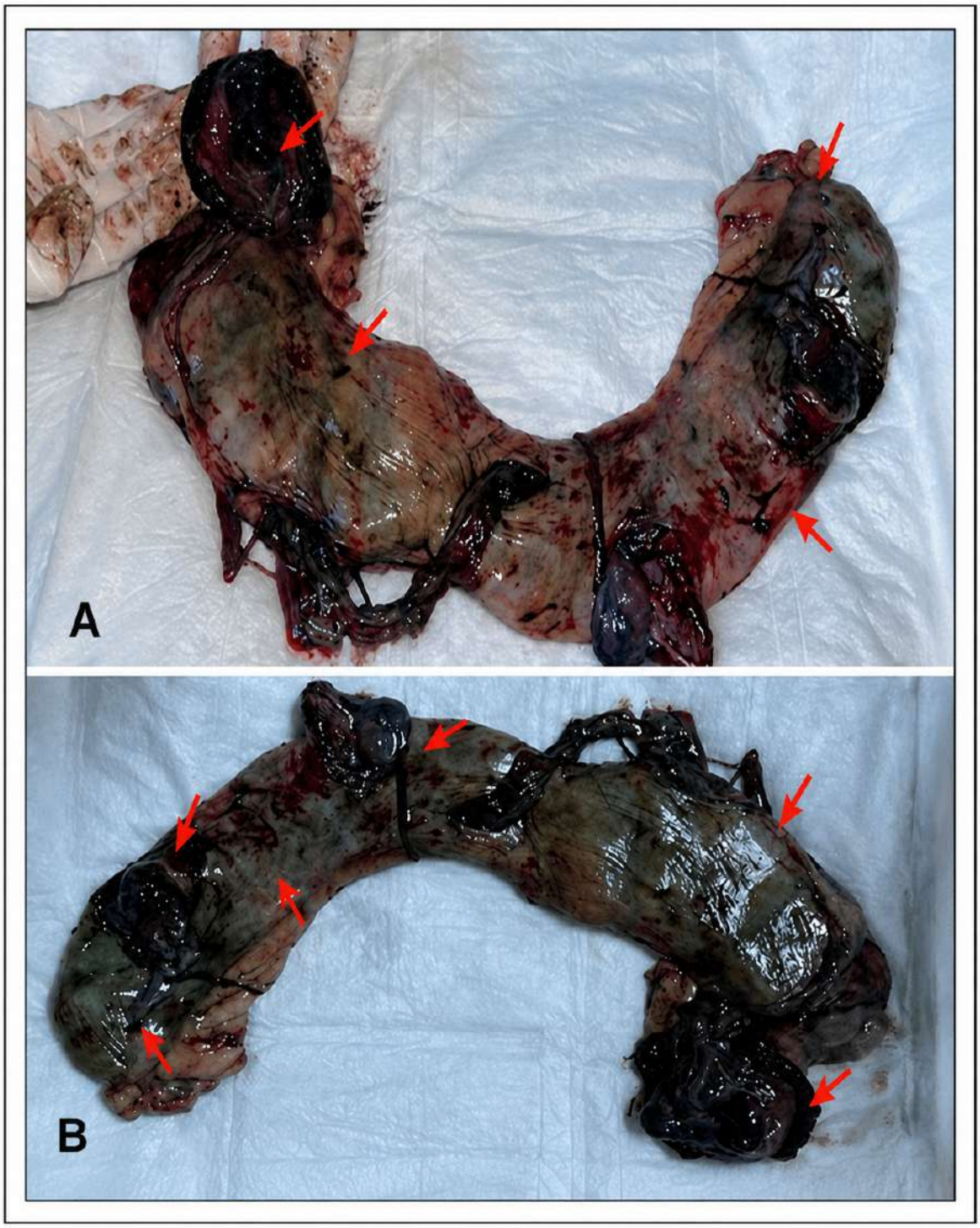


Figure 5. Necrotic areas in postoperative fetal membranes (red arrow).

A routine ovariohysterectomy was then performed. After haemostasis was achieved, the abdominal cavity was closed according to its anatomical layers (linea alba, subcutaneous tissue,

and skin). A dressing was applied to the area. The tumour mass located in the vagina was excised using cautery after catheterisation of the bladder **(Figure 6. AB).**

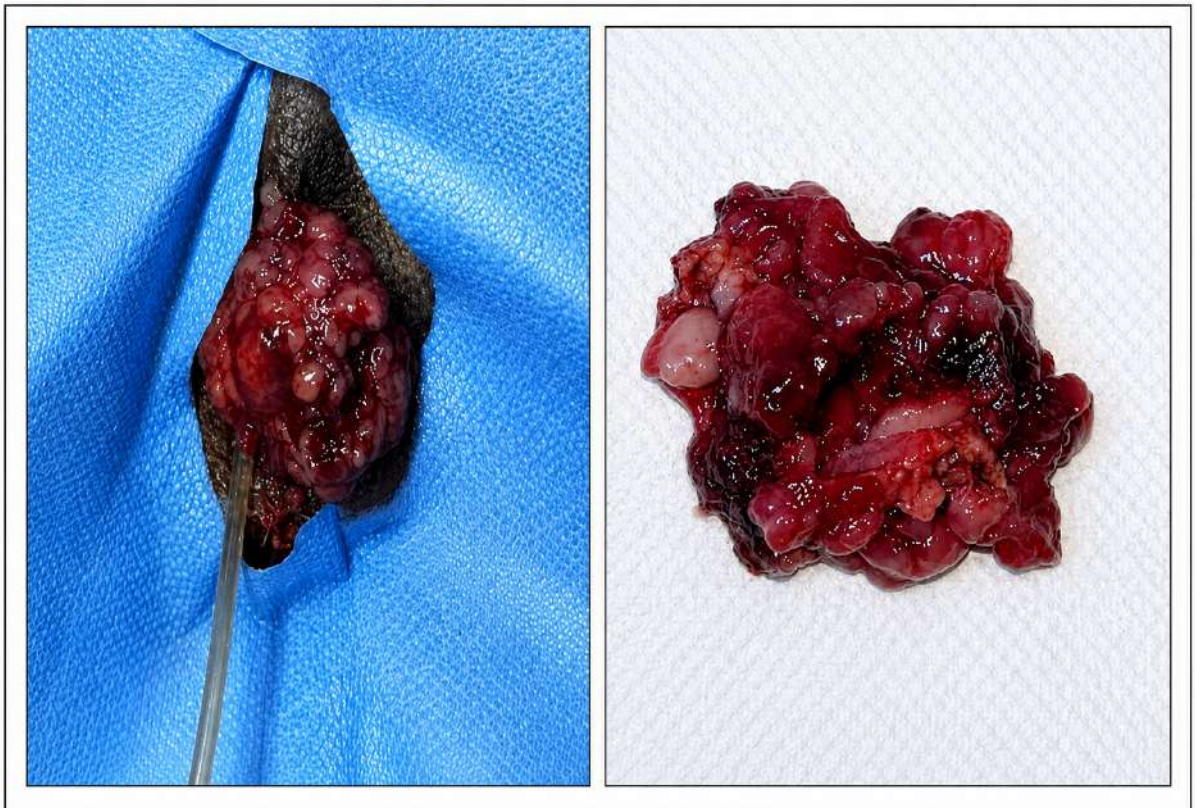


Figure 6. (A) Appearance of the mass after the biopsy procedure. **(B)** Appearance of the excised tumour mass.

In the postoperative period, to prevent the risk of secondary infection, a broad-spectrum combination antibiotic regimen was administered: Metronidazole (Polygl 0.5%, Polifarma, Turkey) (IV) at 10 mg/kg and Enrofloxacin (Baytril-K 5%, 50 ml, Bayer/Elanco, Turkey) at 5 mg/kg (IM) for 7 days. To control pain and inflammation, a non-steroidal anti-inflammatory analgesic, Meloxicam (Meloxicam, 100 ml, Bavet İlaç, Turkey), was prescribed at 0.2 mg/kg (SC). The patient was monitored for postoperative complications and supported with fluid and electrolyte therapy. On the 14th day post-surgery, following suture removal, treatment with vincristine sulphate (Vincristine, 2 mg/2 ml IV, Koçak Farma Pharmaceuticals, Turkey) at a dose of 0.025 mg/kg was initiated, and full clinical recovery was achieved during the follow-up period.

3. Discussion

Vincristine sulphate chemotherapy is an effective and widely used method for treating TVT in dogs (Den Otter et al. 2015, Pimentel et al. 2025). However, the administration of chemotherapy during pregnancy, particularly during the organogenesis period, carries a risk of teratogenic effects

and abortion in relation to foetal development (Autio et al. 2007, Kaya et al. 2025). The coexistence of pregnancy and neoplastic diseases is rare in veterinary medicine, with current knowledge largely based on a limited number of case reports (Cardonick and Iacobucci 2004, Farhana et al. 2024). Rare reproductive pathologies associated with pregnancy in dogs often present with nonspecific clinical signs, and diagnosis is typically made using imaging methods. Gözer et al. (2024) identified an extrauterine pregnancy following radiographic examination in the postpartum period and reported that surgical exploration is crucial for both diagnosis and treatment. Mechanical obstruction caused by a TVT in the birth canal can lead to dystocia. Additionally, the tumour's fragile and vascular structure may increase the risk of bleeding, oedema, and inflammation during delivery, thereby complicating the birthing process (Johnston et al. 2001). In the present case, a TVT mass localised in the vaginal region was considered a primary factor in the development of dystocia. The foul-smelling and turbid amniotic fluid observed during surgery, along with degenerative changes in the fetal membranes, supported the diagnosis of an intrauterine infection; this condition was assessed to have contributed to fetal hypoxia and intrauterine fetal death. Additionally, the presence of marked leukocytosis supports a systemic inflammatory response (Das and Das 2000). In such cases, performing an oophorohysterectomy in conjunction with a caesarean section is considered appropriate for both the removal of infected uterine tissue and the prevention of potential recurrences. In the case presented, after postoperative recovery from the caesarean section and ovariectomy, chemotherapy with vincristine (0.025 mg/kg IV) was initiated, and haematological parameters were monitored weekly. Treatment was discontinued when no TVT cells were detected in vaginal cytology at the end of the fourth cycle. This approach is consistent with treatment protocols recommended in the literature (Ganguly et al. 2016).

5. Conclusion

This case demonstrates that TVT should not be regarded merely as a localised genital tumour during pregnancy. TVT can cause serious obstetric complications through mechanical obstruction, systemic infection, and intrauterine pathologies. Therefore, early diagnosis, regular obstetric monitoring, and appropriate surgical and chemotherapeutic management are crucial for protecting maternal and fetal health in pregnant dogs with suspected TVT.

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ENTREPRENEURSHİP EDUCATİON AS A TOOL FOR BİODİVERSİTY CONSERVATİON: IMPLİCATİONS FOR CURRİCULUM REFORM İN TERTİARY INSTİTUTİONS İN RİVERS STATE, NİGERİA

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ABSTRACT

This study empirically examined entrepreneurship education as a strategy for enhancing biodiversity conservation and explored its implications for curriculum reform in tertiary institutions in Rivers State, Nigeria. A descriptive survey research design was adopted. The population comprised undergraduate biology students and biology education lecturers in selected tertiary institutions. Using stratified random sampling, 170 respondents (150 students and 20 lecturers) were selected. Data were collected using a structured questionnaire titled Entrepreneurship Education and Biodiversity Conservation Questionnaire (EEBCQ). Descriptive statistics (mean and standard deviation) and inferential statistics (independent samples t-test) were employed at 0.05 level of significance. Findings revealed that entrepreneurship education significantly improved students' awareness of biodiversity conservation ($t = 6.21$, $p < 0.05$) and enhanced readiness for biodiversity-based enterprises. However, existing biology curricula were found inadequate in integrating practical entrepreneurial components. The study concludes that curriculum reform integrating entrepreneurship with biodiversity education can promote sustainable livelihoods and environmental stewardship.

Keywords: Entrepreneurship education, biodiversity conservation, curriculum reform, biology education, Rivers State.

Introduction / Background of the Study

Biodiversity is the variety of living organisms within ecosystems it is fundamental to ecological balance, human survival, and sustainable development. It provides essential ecosystem services such as food production, climate regulation, pollination, and medicinal resources. However, biodiversity across the globe is declining at an alarming rate due to anthropogenic activities such as deforestation, pollution, overexploitation of natural resources, and climate change (Convention on Biological Diversity [CBD], 2020). In Nigeria, and particularly in Rivers State, these threats are intensified by oil exploration, gas flaring, urban expansion, and unsustainable agricultural practices (Ayanlade & Drake, 2020).

Rivers State, located in the Niger Delta region, is one of the most ecologically diverse areas in Nigeria, characterized by mangrove forests, freshwater swamps, and rich wildlife. Despite this ecological richness, the region faces severe environmental degradation, leading to loss of biodiversity and reduced ecosystem productivity. The economic dependence on oil has further contributed to environmental neglect, making conservation efforts more challenging (UNEP, 2021). Consequently, there is a growing need for innovative and sustainable strategies that integrate environmental conservation with economic empowerment.

One such strategy is entrepreneurship education. Entrepreneurship education has emerged as a critical tool for equipping individuals with the skills, knowledge, and competencies needed to identify opportunities, create enterprises, and contribute to economic development (Neck & Greene, 2018). In the context of biodiversity conservation, entrepreneurship education can empower students to develop eco-friendly businesses such as sustainable agriculture, aquaculture, beekeeping, and eco-tourism. These ventures not only generate income but also promote the sustainable use and conservation of biological resources (Adeola, 2021).

The integration of entrepreneurship education into biology education is particularly important in tertiary institutions, where students acquire specialized knowledge that can be transformed into practical solutions. Biology education provides learners with an understanding of ecosystems, species interactions, and environmental sustainability. However, without entrepreneurial skills, this knowledge often remains theoretical and underutilized (Okoli & Eze, 2022). By incorporating entrepreneurship into biology curricula, students can be encouraged to apply their scientific knowledge to real-world challenges, thereby fostering innovation and self-reliance.

In Nigeria, the Federal Government has recognized the importance of entrepreneurship education and has made it a compulsory component of tertiary education. Despite this policy initiative, the implementation has faced several challenges, including inadequate curriculum integration, lack of practical training, insufficient funding, and limited collaboration with industry stakeholders (Okechukwu & Nwankwo, 2021). As a result, many graduates lack the skills required to translate their academic knowledge into viable business ventures, particularly in the area of biodiversity conservation.

Furthermore, the current biology curriculum in many tertiary institutions in Rivers State does not adequately incorporate practical entrepreneurial components. Teaching methods are often lecture-based, with minimal emphasis on experiential learning, fieldwork, and innovation. This gap limits students' ability to develop competencies necessary for biodiversity-based enterprises. Studies have shown that experiential learning approaches, such as project-based learning and internships, significantly enhance students' entrepreneurial skills and environmental awareness (Ezeudu & Okeke, 2020).

The need for curriculum reform is therefore imperative. Curriculum reform involves revising and updating educational content, teaching methods, and assessment strategies to meet contemporary societal needs. Integrating entrepreneurship education into biodiversity conservation within the biology curriculum can serve as a pathway for achieving sustainable development. It aligns with global initiatives such as the United Nations Sustainable Development Goals (SDGs), particularly Goal 4 (Quality Education), Goal 8 (Decent Work and Economic Growth), and Goal 15 (Life on Land) (UNESCO, 2021).

Empirical evidence suggests that students exposed to entrepreneurship education demonstrate higher levels of innovation, critical thinking, and problem-solving skills. They are also more likely to engage in self-employment and entrepreneurial activities (Neck & Greene, 2018). In the context of biodiversity conservation, this translates into increased participation in environmentally sustainable practices and enterprises. However, there is limited empirical research examining the specific relationship between entrepreneurship education and biodiversity conservation in Rivers State.

This study therefore seeks to fill this gap by examining how entrepreneurship education influences students' awareness of biodiversity conservation and their readiness to engage in biodiversity-based enterprises. It also explores the extent to which current biology curricula support this integration and identifies areas for improvement.

By providing empirical evidence, the study aims to inform policymakers, educators, and curriculum developers on the need for integrating entrepreneurship education into biology programs. Such integration has the potential to not only enhance biodiversity conservation but also address unemployment and promote sustainable livelihoods among graduates. other aquatic ecosystems. It plays a crucial role in maintaining ecological balance and supporting human livelihoods. Ecosystem services such as nutrient cycling, climate regulation, pollination, and food production depend heavily on biodiversity (CBD, 2020). However, global biodiversity is declining rapidly due to human-induced pressures such as deforestation, pollution, climate change, and industrialization.

In Nigeria, biodiversity loss is particularly pronounced in the Niger Delta region, including Rivers State. The region is characterized by rich ecosystems such as mangrove forests, freshwater swamps, and diverse wildlife. Despite this richness, oil exploration activities, gas flaring, and urban

expansion have led to environmental degradation and loss of biodiversity (Ayanlade & Drake, 2020; UNEP, 2021).

Addressing biodiversity loss requires innovative strategies that combine environmental conservation with economic empowerment. One such approach is entrepreneurship education, which equips individuals with skills for innovation, opportunity recognition, and enterprise development (Neck & Greene, 2018). Entrepreneurship education has gained global recognition as a tool for sustainable development, particularly in developing countries where unemployment rates are high.

Integrating entrepreneurship education into biodiversity conservation enables students to develop eco-friendly enterprises such as sustainable agriculture, aquaculture, beekeeping, and eco-tourism (Adeola, 2021). These enterprises contribute to both environmental sustainability and economic growth.

However, the biology curriculum in many Nigerian tertiary institutions remains largely theoretical, with limited emphasis on practical skills and entrepreneurship (Okoli & Eze, 2022). This gap hinders students' ability to translate knowledge into real-world solutions.

Therefore, this study examines the role of entrepreneurship education in enhancing biodiversity conservation and explores its implications for curriculum reform in Rivers

Review of Related literatures

Concept of Entrepreneurship Education

Entrepreneurship education refers to the process of equipping individuals with knowledge, skills, and attitudes necessary for creating and managing business ventures (Neck & Greene, 2018). It emphasizes innovation, creativity, and risk-taking.

According to Okechukwu and Nwankwo (2021), entrepreneurship education in Nigeria aims to address unemployment and promote self-reliance among graduates. It has been integrated into tertiary education as a compulsory course, but its effectiveness depends on implementation strategies.

Modern entrepreneurship education goes beyond theoretical instruction to include experiential learning, business simulations, and real-world problem-solving (Fayolle & Gailly, 2015). This approach is essential for developing practical competencies among graduates.

Biodiversity Conservation

Biodiversity conservation involves protecting and managing biological resources to ensure sustainability. It includes in-situ and ex-situ conservation strategies (CBD, 2020).

In Nigeria, biodiversity conservation faces challenges such as habitat destruction, pollution, and climate change. The Niger Delta region is particularly vulnerable due to oil-related activities (UNEP, 2021).

Scholars argue that conservation efforts must incorporate local communities and economic incentives to be effective (Adeola, 2021). So relating to this study, therefore is a need to incooprate entrepreneurship as a tool for proper biodiversity conservation in the country.

Entrepreneurship and Biodiversity Conservation

The integration of entrepreneurship into biodiversity conservation promotes sustainable livelihoods. Eco-entrepreneurship involves business activities that contribute to environmental sustainability.

Examples include:

- Organic farming
- Beekeeping
- Eco-tourism
- Wildlife conservation enterprises

These activities generate income while preserving natural resources (Schaltegger & Wagner, 2011).

Studies show that entrepreneurship education enhances environmental awareness and encourages sustainable practices (Adeola, 2021).

Biology Education and Sustainable Development

Biology education plays a critical role in promoting environmental awareness. It provides knowledge about ecosystems, biodiversity, and conservation.

However, traditional teaching methods often focus on theoretical knowledge, limiting practical application (Okoli & Eze, 2022). Integrating entrepreneurship into biology education can enhance its relevance and impact.

Curriculum Reform in Tertiary Education

Curriculum reform involves updating educational content to meet current societal needs. In Nigeria, there is a growing call for integrating entrepreneurship into science education (Ezeudu & Okeke, 2020).

Effective curriculum reform should include:

- Practical training
- Industry collaboration
- Experiential learning
- Innovation hubs

Empirical Studies

Several studies have examined the relationship between entrepreneurship education and sustainable development.

- Adeola (2021) found that entrepreneurship education enhances environmental sustainability awareness.
- Okechukwu and Nwankwo (2021) reported increased self-employment among graduates exposed to entrepreneurship training.
- Ezeudu and Okeke (2020) emphasized the importance of curriculum reform in science education.

However, limited studies focus specifically on biodiversity conservation in Rivers State, creating a gap that this study addresses as the researcher states " that using entrepreneurship as a tool for biodiversity conservation will increase employerability among graduates, create confidence in individuals after school to face the society and also self-reliance.

Methodology

This study adopted Descriptive survey design , The population of the study consisted of all undergraduate biology students and biology education lecturers in selected tertiary institutions in Rivers State, totaling 1,280 individuals. From this population, a sample of 170 respondents (150 students and 20 lecturers) was selected using stratified random sampling. The instrument used for the study is a structured questionnaires titled " Entrepreneurship Education and Biodiversity Conservation Questionnaire (EEBCQ) " was structured by the researcher to gather information from the respondents. The reliability of the instrument was validated and tested at 0.82 Cronbach Alpha and datas collected were analyzed using mean, standard deviation and t-test.

Results :

Table 1: Mean and Standard Deviation on Biodiversity Awareness

Group.	**N.**	**Mean.**	**Std. Deviation**
Exposed to Entrepreneurship Education.	**150**	**3.85**	**0.62**
Not exposed.	**150**	**2.91**	**0.74**

Interpretation: Exposure to entrepreneurship education improves biodiversity awareness.

Table 2: Independent Samples t-test

Variable.	t	Df.	p-value.	Decision
Biodiversity awareness.	6.21	168	0.000	Significant

Interpretation: There is a significant difference ($p < 0.05$).

Table 3: Readiness for Biodiversity-Based Enterprises

Item. .	Mean.	Std. Dev.	Decision
Eco-business interest.	3.72	0.68	Agree
Beekeeping	3.60	0.71	Agree
Organic farming.	3.81	0.65	Agree
Eco-tourism.	3.54	0.73	Agree

Cluster Mean = 3.675

Table 4: Curriculum Adequacy

Item.	*Mean.*	*Std. Dev.*	*Decision*
Entrepreneurship Inclusion.	*2.45*	*0.80*	*Disagree*
Practical training.	*2.30*	*0.76*	*Disagree*

Industry collaboration 2.18 0.82 Disagree

Cluster Mean = 2.31

Discussion of Findings

The study revealed that entrepreneurship education significantly enhances students' awareness of biodiversity conservation. This aligns with previous studies indicating that entrepreneurship fosters innovation and environmental responsibility (Adeola, 2021; UNESCO, 2021).

The high readiness for biodiversity-based enterprises suggests that students are willing to apply their knowledge practically. However, the inadequacy of the current curriculum highlights a critical gap. Without practical exposure, students may lack the competencies required for real-world application. However, curriculum gaps remain a major challenge.

Implications for Curriculum Reform

- Integration of entrepreneurship into biology courses
- Development of practical training programs
- Establishment of incubation centers
- Strengthening industry partnerships

Conclusion

Entrepreneurship education is essential for promoting biodiversity conservation and sustainable development. Curriculum reform is necessary to maximize its impact.

Recommendations

- Government should fund curriculum innovation
- Institutions should adopt experiential learning
- Students should engage in eco-entrepreneurship

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AI-DRIVEN CATALOGUING AND CLASSIFICATION SERVICES IN ACADEMIC LIBRARIES IN A DIGITAL ECONOMY

A Conference Paper Submitted to the Annual International Conference on Library and Information Science

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ABSTRACT

The blistering development of the technologies of the artificial intelligence (AI) is radically changing the services of cataloguing and classifying in academic libraries against the background of the changing digital economy. The given paper analyses the way in which AI-based applications, such as machine learning (ML), natural language processing (NLP), and semantic web technologies, are changing the conventional role of bibliographic organization in academic libraries. The research paper is based on a systematic review approach, which will use peer-reviewed academic articles, institutional reports, and statistical data published in 2019-2025. Critical results have shown that AI-assisted cataloguing can save up to 60 percent of cataloguing hour, with the subject heading accuracy of 8993 percent congruence with professional cataloguers. The digital economy has intensified the need to have more machine-readable and rich metadata, linked data infrastructure, and scalable cataloguing processes that can manage digital collections that are growing exponentially. Nevertheless, there are major obstacles such as algorithmic discrimination, unhealthy legacy data, skills deficit among the workforce, and lack of funding-especially in Global South libraries. The paper suggests the human-AI interaction model, a gradual implementation plan, the strong data governance system, and AI literacy investment to catalog professionals. The results highlight the idea that AI-based cataloguing is not a technological refinance but a strategic change of focus that is necessary to fulfill the knowledge management requirements of the twenty-first century digital economy.

Keywords: Artificial Intelligence, Academic Libraries, Cataloguing, Classification, Digital Economy, Machine Learning, Natural Language Processing, Library Automation

1. Introduction

Academic libraries are centrally located in the set of knowledge infrastructure of institutions of higher learning. Since they are the stores of academic materials and are both the portals to information networks throughout the world, they are required to manage, maintain, and share knowledge in manner that enhances teaching, learning, as well as research. Cataloguing and classification are some of the fundamental technical services in an academic library and have traditionally been labour intensive, time intensive and expensive services. The development of bibliographic records, the assignment of subject headings, and the use of classification schemes, including the Dewey Decimal Classification (DDC) and Library of Congress Classification (LCC), have always been very labor-intensive procedures under the guide of the established standard, including Resource Description and Access (RDA) and the Machine-Readable Cataloguing (MARC) format (Yusuf & Iwu-James, 2022).

The data-driven operations, cloud computing, platform ecosystems and algorithmic decision-making that have led to the emergence of the digital economy have placed new pressure and opportunities unparalleled by any other academic library. The library technology market has experienced a massive demand both in 2020 and 2025 and that library systems based on AI are expected to show compound annual growth rate (CAGR) of 26.4 percent between 2022 and 2030 (Grand View Research, 2023). This has changed the face of libraries since they have been forced to consider artificial intelligence as a means of improving the efficiency, accuracy, and scalability of cataloguing.

AI-based cataloguing systems take advantage of technologies of ML, NLP, computer vision, and knowledge graphs to automatically generate and enhance bibliographic metadata. Possibilities laid out by platforms like OCLC WorldShare Metadata or exLibris Alma (or newer AI-based offerings), are making possible new definitions of what is technically capable in workflow cataloguing. Research shows that AI-based cataloguing may cut the cataloguing length by as much as 60% and keep or enhance the quality of metadata (Breeding, 2023; Ullah and Ameen, 2020). Although these developments have been made, there are challenges associated with the idea of integrating AI in academic library cataloguing. Algorithms bias, poor quality of data, reskilling the workforce, and financial limitations are still problematic to adoption, especially when it comes to libraries in the Global South (Okonkwo & Nwosu, 2024).

The research question that will inform the paper is as follows: How are AI-based cataloguing and classification systems changing the technical services of academic libraries in the digital economy, and what are the strategies to make them successful and fair? The given question is investigated using three sub-questions: (1) What AI technologies do academic libraries use in cataloguing, and what are the results? (2) What has changed in terms of cataloguing/classification in the digital economy? (3) What are the major challenges to the adoption of AI cataloguing, and which evidence-based strategies can overcome them?

The paper continues in the following way: Section 3 will review the literature on the topic and pinpoint research gaps. The methodology is presented in section 4. In section 5, the findings are

given in the major areas of theme. Section 6 provides insights into the ramification of the findings in respect to the available literature. Section 7 ends with conclusion of the major findings, limitations and future research recommendations.

2. Literature Review

2.1 Academic Libraries and Cataloguing in the Digital Age

Academic libraries are mission-driven organisations that base their collections, services, and operational strategies on the academic disciplines and research agendas of their parent organisations (Adeniran, 2020). The bibliographic base that the users of library resources rely on in discovering library resources is their technical services operations, which includes acquisitions, cataloguing, classification, and authority control. According to Iwhiwhu and Okorodudu (2022), it is the quality of the cataloguing service that makes the difference in the ability of the users to find and acquire the library materials, which makes the strategic nature of the cataloguing service investment.

The standards of traditional cataloguing are controlled by internationally-recognized standards: the MARC format, which has bibliographic data in a machine-readable format; RDA, which gives the content standard to describe it; and the Library of Congress Subject Headings (LCSH), which gives the controlled vocabulary to search by. According to Mugisha and Zhang (2022), the accuracy of subject classification by experienced cataloguers varies between 87 and 94 percent, depending on the complexity of the subject domain, and they noted the nature of the problem of the lack of uniformity in the quality of manual cataloguing at scale.

The digital economy has radically changed the conditions of the functioning of academic libraries. According to Corrall (2019), academic libraries have to transform themselves into active agents of the digital knowledge economy instead of remaining passive guardians of the physical collections. This repositioning needs new technical infrastructures, such as AI-based cataloguing systems, linked data models, and cloud-based platforms of library services (Breeding, 2023).

2.2 AI Technologies in Library Cataloguing

The use of artificial intelligence in the cataloguing of libraries has enjoyed increasing academic interest since around 2017, faster progress in empirical studies since 2020. Lavoie et al. (2019) offered a preliminary conceptual model of the understanding of the so-called evolving scholarly record and technological requirements of it to library cataloguing systems with the two most transformative agents of the future of bibliographic organization identified as AI and linked data.

Machine learning based cataloguing methods have shown some potential. A note of Loth, Liu, and Ng (2020) found an accuracy of 82 to 91 percent on well-represented subject areas with ML models trained on OCLC WorldCat records, but attributed accuracy to 65 to 72 percent in interdisciplinary fields. Suominen and Toivonen (2022) further developed this study on the transformer-based deep learning models with a higher accuracy of more than 93% in the first level classification at limited areas. All these studies make it clear that ML is capable of doing basic

classification tasks with acceptable accuracy to aid production cataloguing processes, especially with human quality inspection.

The use of NLP in cataloguing has also increased. A pilot study by Chen and Williams (2024) in a large research university library library reported that NLP-aided cataloguing took half as much time as subject analysis and that it had an 89% agreement with expert cataloguers regarding subject heading assignment. Hossain and Islam (2023) conducted a systematic review of ethical aspects of AI in library services and cited transparency, bias, and accountability as the three critical issues on ethics that need to be addressed in the policy.

Solving the problem of algorithmic bias in AI cataloguing has become an important field of academic interest. Drabinski (2019) recorded the bias inherent to LCSH and contended that the inequities will be perpetuated and amplified by AI systems that have been trained on biased bibliographic information. Oluwole, Oyelaran, and Adeyemi (2021) have presented empirical data, discovering that AI classification systems that are trained with a bulk of English-language samples delivered a lower accuracy of products in African languages by 31-42 percent with critical consequences relating to equity of access in academic libraries in the Global South.

2.3 Digital Economy Impact on Library Services

The effects of the digital economy on library cataloguing work through various ways. The digital collections explosion has led to new cataloguing needs: electronic resources now constituted 72% of collection spending by the members of the ARL, compared to 43% in 2012 (ARL, 2023). The resilience of cloud-based cataloguing infrastructure was reported when Hanson and Hessel (2021) recorded the spread of the COVID-19 pandemic accelerating the digital shift of library technical services. Research Data Alliance (2023) discovered that 68% of academic libraries had developed or were developing research data management services, and metadata creation of datasets was cited as one of the main cataloguing issues.

The transition to linked data models is a pivotal point of need in the digital economy and cataloguing innovation. Netanel (2024) conducted a survey of BIBFRAME implementation in US academic libraries and discovered that 43 percent of academic libraries had active implementation projects as of 2024, against 8 percent in 2019. This rapid expansion indicates the technical benefits of linked data to AI processing of the data and the competitive threat posed by web-scale discovery systems that can only effectively exploit library metadata when it is formatted as linked data.

2.4 Research Gaps

Although more literature has been developed on the use of AI in library cataloguing, there are a number of gaps that are important. To begin with, majority of the empirical research has been carried out at well-equipped research libraries in North America and Europe, with very few results on academic libraries in Africa, Asia, and Latin America (Eze & Nwosu, 2021; Okonkwo & Nwosu, 2024). Second, there is a lack of longitudinal research such as that of the long-term performance of AI cataloguing systems, and how they affect the quality of catalogues and user discovery. Third, workforce consequences of AI adoption such as the evolving skills of cataloguing

professionals and professional transition management strategies are underexplored theoretically. This essay attempts to fill these gaps by reviewing the evidence in different geographic settings and giving a unified analysis of the technological, organizational and strategic aspects of AI adoption of the cataloguing adoption.

3. Methodology

3.1 Research Design

The study presented in this paper follows the systematic review and documentary analysis methodology, which is aligned with the existing ways of research in the field of library and information science to synthesize evidence on technology adoption and professional practice. This study is specifically suitable to systematic review since the AI cataloguing technology is rapidly changing, the relevant literature is spread across library science journals, computer science journals, and information systems journals, and there is no primary infrastructure of the study to collect empirical data at the level of geographic and thematic coverage (Bawden and Robinson, 2023).

3.2 Data Sources and Search Strategy

Literature search was carried out by using systematic search of the following databases: Library, Information Science and Technology Abstracts (LISTA), Web of Science, Scopus, Google Scholar, and ProQuest Library and Information Science. The following lists of keywords were used in searches: ('artificial intelligence' OR machine learning' OR natural language processing) AND (cataloguing' OR cataloging' OR classification) AND (academic libraries' OR university libraries); ('digital economy' OR digital transformation) AND (library technical services' OR bibliographic metadata); and ('AI bias' OR algorithmic bias) AND (library cataloguing' OR bibliographic records). Besides the literature sources that are peer reviewed, grey literature such as the Association of Research Libraries (ARL), OCLC Research, the International Federation of Library Associations (IFLA), the Association of College and Research Libraries (ACRL), and key vendors of library technologies were also searched and included.

3.3 Inclusion and Exclusion Criteria

The publications were included based on the following criteria: (1) the publication date must be January 2019 or later; (2) the publication must use AI, machine learning, or NLP applications in library cataloguing, classification, or metadata management; (3) the publication must discuss or at least mention academic or research libraries; and (4) the publication must be in English. Publications were also eliminated because it focused on public library or special library situations only and these were not relevant to the academic context, and they were opinion pieces lacking empirical support or theoretical frameworks. In the first search, 147 items were located; 42 items were selected after inclusion/exclusion criteria and the quality assessment were applied to continue with substantive analysis.

3.4 Data Analysis

They were analyzed using thematic analysis of retained sources, and the identified themes were found both deductively (through the research questions) and inductively (through the patterns found in the literature). Statistically reported, surveyed and empirical data on AI were extracted and tabulated to allow comparative analysis of AI cataloguing adoption rates, performance indicators and prevalence of challenges among institutional and geographical settings. The results are described in thematic format instead of study-by-study format to offer a cohesive synthesis of findings instead of a descriptive catalogue of studies.

4. Results

4.1 Nature and Services of Academic Libraries in the Digital Economy

Academic libraries are institutional organizations that have been integrated into higher education institutions and are characterized by directness to curricula, research interests, and the official needs of academic activity (Adeniran, 2020). The common academic library has technical (cataloguing, acquisitions, preservation), public (reference, circulation, information literacy), and digital/emerging (institutional repositories, research data management, digital humanities support) service activities. As stated in the ARL Statistics Report 20222023, the average number of professional and support staff in ARL member libraries is 247, and the collection has more than 10 million volumes, with electronic resources taking 72% of the collection spending (ARL, 2023).

Academic libraries have become increasingly hybridized, yet 94 percent of ARL libraries have increased digital services in 20202021 (ARL, 2021). Traditional Integrated Library Systems have been supplanted by Library services Platforms (LSP) such as OCLC WorldShare Management Services, ExLibris Alma and Innovative Interfaces Polaris, of which 67 per cent of North American academic libraries had migrated to cloud-based LSPs by 2023 (Breeding, 2023). Table 1 provides an overview of the service types and possibilities of AI use in the processes of the academic library.

Table 1: Academic Library Service Categories and AI Application Potential

Service Category	Key Functions	AI Application Potential	Current Adoption Level
Technical Services	Acquisitions, Cataloguing, Classification, Authority Control	Very High — automated metadata, record creation	54% of ARL libraries (ALA, 2024)
Public Services	Reference, Circulation, ILL, Information Literacy	Moderate — chatbots, recommender systems	38% (chatbot/virtual reference)
Digital Services	Repositories, ERM, Data Curation, Digital Preservation	High — automated ingest, metadata enrichment	42% (repository AI tools)
Research Services	Data Management, Scholarly Communication, OER	Growing — AI metadata for datasets	31% (data management AI)

4.2 Cataloguing and Classification Services: Current State

Catalogue in academic libraries is still based on internationally accepted standards, but they are being supplemented by AI tools. MARC21 remains in use in most academic libraries around the world, and RDA is in use in about 75% of ARL libraries as the main standard of content. As a successor to MARC, BIBFRAME is actively implemented in 43% of academic libraries in the US, as of 2024, whereas in 2019 the figure was 8% (Netanel, 2024). Table 2 shows the most important cataloguing standards and their AI suitability.

Table 2: Cataloguing Standards, Adoption Rates, and AI Compatibility

Standard/Framework	Purpose	Global Adoption (2024)	AI Compatibility
MARC21	Bibliographic data encoding	~90% of academic libraries	Moderate
RDA	Content description standard	~75% of ARL libraries	High

Standard/Framework	Purpose	Global Adoption (2024)	AI Compatibility
BIBFRAME	Linked data bibliographic model	~43% (implementation projects)	Very High
LCSH	Subject heading authority control	Predominant (English-language)	High
LCC	Classification scheme	~85% of US academic libraries	Moderate
DDC	Universal decimal classification	~200,000 libraries worldwide	Moderate
VIAF	International authority file	60+ million records (2023)	High

4.3 AI Technologies Applied in Cataloguing

The systematic review recognized seven main types of AI technology used in academic library cataloguing, including machine learning, NLP, computer vision, deep learning, knowledge graphs, large language models, and AI-based recommender systems. These technologies along with their usage, performance standards, and exemplary platforms are brought out in Table 3.

Table 3: AI Technologies Applied in Cataloguing and Classification (2019–2024)

AI Technology	Cataloguing Application	Performance Benchmark	Representative Platform
Machine Learning (ML)	Classification number prediction, copy matching	82–91% accuracy (Loth et al., 2020)	OCLC Classify, WorldShare Metadata
Natural Language Processing	Subject heading extraction, keyword indexing	89% expert agreement (Chen & Williams, 2024)	EBSCO AI Metadata, Alma AI
Large Language Models	Metadata enrichment, descriptive cataloguing	89–93% subject accuracy	GPT-4-based tools, Claude

AI Technology	Cataloguing Application	Performance Benchmark	Representative Platform
Computer Vision / OCR	TOC extraction, retrospective conversion	73% cost reduction (Library of Congress, 2024)	Google Vision API, ABBYY
Knowledge Graphs	Entity disambiguation, authority control	VIAF: 60M+ linked entities (VIAF, 2023)	VIAF, Wikidata, Schema.org
Deep Learning / Transformers	Complex subject analysis, multilingual cataloguing	91–95% accuracy (narrow domains)	BERT-based library models
Recommender Systems	Copy cataloguing suggestions, related record retrieval	70–85% cataloguer acceptance rate	OCLC WorldShare, ExLibris Alma

4.4 Impact of the Digital Economy on Cataloguing

Digital economy has resulted in statistically significant changes in the operations of cataloguing in academic libraries. Table 4 shows relevant statistics indicators of the impact of the digital economy on the cataloguing of 2019-2024, compiled based on ARL statistics, survey of vendors, and reports of professional associations.

Table 4: Statistical Indicators of Digital Economy Impact on Cataloguing (2019–2024)

Indicator	2019 Baseline	2023/2024 Value	Change	Source
E-resource share of ARL expenditures	60%	72%	+12 pp	ARL, 2023
Academic libraries using cloud-based LSPs	38%	67%	+29 pp	Breeding, 2023
AI-assisted cataloguing adoption (ARL)	12%	54%	+42 pp	ALA, 2024

Indicator	2019 Baseline	2023/2024 Value	Change	Source
Avg. cataloguing time per item (AI-assisted)	45 min	18 min	−60%	Ullah & Ameen, 2020
Libraries offering research data cataloguing	31%	68%	+37 pp	RDA, 2023
BIBFRAME implementation projects (US)	8%	43%	+35 pp	Netanel, 2024
AI as strategic library priority	18%	76%	+58 pp	EDUCAUSE, 2024
Library technology AI market CAGR	—	26.4% CAGR	Projected 2030	Grand View Research, 2023

4.5 Challenges to AI-Driven Cataloguing

The review has found eight major categories of challenges that hinder the adoption and efficiency of AI cataloguing. The most widespread technical challenge that was found to be universal was data quality flaws in legacy MARC data, which has been built up over decades due to an unevenly practiced cataloguing history and system migrations (Mugisha and Zhang, 2022). Drabinski (2019) and Oluwole et al. (2021) report Algorithmic bias: AI classification systems that were trained on mostly English and Western-centric data set were found to be even 3142% less accurate when presented with African language material. Sixty-six percent of the surveyed cataloguers claimed competency gaps in their workforce, and only 34% were confident in their skills to assess and handle AI cataloguing systems (LISEN, 2023). Table 5 is a summary of the prevalence of challenges.

Table 5: Challenges to AI-Driven Cataloguing — Prevalence and Impact Evidence

Challenge	Prevalence / Statistical Evidence	Primary Impact	Source
Legacy data quality	Major barrier in 68% of libraries	Corrupts AI training data	ACRL, 2024
Algorithmic bias	31–42% accuracy drop for African-language materials	Inequitable cataloguing outcomes	Oluwole et al., 2021
Workforce competency gaps	Only 34% confident managing AI systems	Poor AI oversight quality	LISEN, 2023
Workforce resistance	48% express job displacement concerns	Low adoption rate	Park & Tosaka, 2022
Financial constraints	61% of small libraries cite cost as barrier	Unequal adoption across institutions	ACRL, 2024
Infrastructure (Dev. world)	78% of Nigerian university libraries affected	Digital divide in global librarianship	Okonkwo & Nwosu, 2024
AI explainability	No current industry standard	Undermines cataloguer trust	Hossain & Islam, 2023
Standardization gaps	No universal AI metadata standard (2024)	Interoperability failures	Netanel, 2024

4.6 Strategies for Effective AI Cataloguing Implementation

The review found 6 evidence-based strategy clusters to implement the AI cataloguing effectively. All the strategies were found to have data governance frameworks such as the legacy data remediation, quality standards and structured training data pipelines as essential pre-conditions of all the other strategies. The strongest combined performance results were linked to human-AI collaborative cataloguing models where AI worked on routine tasks with the human cataloguer offering quality control and working on complex materials: 47% time savings with the quality equal to full manual cataloguing (Chen and Williams, 2024). Phased deployment via library consortia was discovered to save per-institution AI tool expenditures by 40 -60% (NERL, 2023), the most practical direction of less resource-intensive libraries. The complete strategic framework is provided in table 6.

Table 6: Evidence-Based Strategies for AI Cataloguing Implementation

Strategy	Key Actions	Evidence of Effectiveness	Priority
Data Governance	Legacy data remediation; quality standards framework	Foundational for all other strategies	Critical
Human-AI Collaboration	Redefine cataloguers as AI supervisors; workflow redesign	47% time saving; equivalent quality (Chen & Williams, 2024)	Critical
Workforce Development	AI literacy training; LIS curriculum reform	Addresses 66% competency gap (LISEN, 2023)	High
Phased Consortium Adoption	Incremental deployment; shared licensing	40–60% cost reduction (NERL, 2023)	High
Ethics & Bias Policies	Bias auditing protocols; transparency standards	Mitigates inequitable outcomes	High
Linked Data Transition	BIBFRAME roadmap; open standards adoption	Future-proofs metadata; enables AI enrichment	Medium

5. Discussion

5.1 AI Cataloguing Performance: Interpreting the Evidence

The performance figures of the AI cataloguing systems that are reported in this review 82-93% classification and 89% subject heading agreement with the expert cataloguers indicate that this has been a notable milestone in comparison with what was possible just five years ago. These numbers, however, must be interpreted in the context. Deep learning models trained on large high-quality datasets have given the highest accuracy rates (9195) in small, well-represented subject domains. Interdisciplinary, new, non-English-language materials especially those where cataloguing has historically been most challenging suffer greatly, and under-cataloguing is most damaging to users (Loth et al., 2020; Oluwole et al., 2021).

These implications of this performance gradient pertain to the introduction of AI cataloguing systems. Instead of taking AI accuracy statistics as equal measures of performance, the library managers ought to do domain-specific performance audits to determine which areas of performance AI support may be trusted to a degree that it does not need human intervention, and in which areas the AI recommendations have to undergo verification to a significant extent. The result of Suominen and Toivonen (2022) that in narrow domains, transformer-based models demonstrate 91-95% accuracy but in larger or interdisciplinary situations, the accuracy decreases gives a useful framework of this discriminated deployment strategy.

The 60 percent change in the time of cataloguing that Ullah and Ameen (2020) and, later on, Chen and Williams (2024) reported was an epigenetic gain in the operational efficiency. This efficiency dividend is vital to academic libraries that are experiencing budgetary constraints and an increase in collection volumes. Nevertheless, there is also an indication that savings in time that have not been properly quality assured may result in lower metadata quality that diminish user discovery-a false economy that cancels the very reasoning behind AI investment. Human-AI collaborative model that drives the savings of time towards quality review instead of reducing the number of people seems to be the most compatible model with the necessity to retain the quality of cataloguing and gain the efficiency advantages.

5.2 Digital Economy Pressures and Library Responses

The 42 percentage-point growth in the adoption of AI cataloguing in ARL libraries in 2019-2024 can signify both real progress in the use of AI tools and the mounting pressure on the digital economy. The competition of library catalogs as the main gateway to discovery is growing among the commercial discovery platforms Google Scholar, Semantic Scholar and research-specific recommendation engines. Nicholas et al. (2022) discovered that 64% of academic researchers in the UK relied on Google Scholar as their discovery tool, in contrast to 28% who relied on their library catalog. This competitive environment is the reason why library administrators have radically increased AI as a strategic priority (18% in 2019, to 76% in 2024, according to EDUCAUSE, 2024): libraries which are unable to compete with the discovery experience provided by commercial platforms will be irrelevant.

The most fundamental structural response to this competitive pressure is the shift to linked data and BIB Francisco. Codifying bibliographic records as linked data allows libraries to make their cataloguing information processable by web-scale systems, allowing library records to be displayed in search results and be exploited by AI applications in such manners as MARC records cannot facilitate. This strategic logic is reflected in the fact that as Netanel (2024) documents, the number of implementations of BIBFRAME has increased by 8 to 43 per cent since 2019. Nevertheless, there is also a heavy investment cost involved in the transition itself and it generates a short-term complexity of operations which restricts the rate of adoption in resource-constrained settings.

5.3 Equity and the Global Dimension

Maybe the most glaring disparity in the existing AI listing situation is the utter inequality between academic libraries that are well-endowed in developed nations and those of the Global South. The observation made by Okonkwo and Nwosu (2024) that 78% of university libraries in Nigeria do not have the ICT infrastructure to support AI cataloguing, and 85% lack sufficient financial resources, is representative of a trend recorded in sub-Saharan Africa and other developing parts of the world (Eze & Nwosu, 2021). This disparity in infrastructure poses a risk of establishing a two-tiered global librarianship whereby libraries in rich institutions acquire compounding productivity and quality benefits out of AI, whereas libraries in less-resourced institutions become further and further disadvantaged.

These equity issues are compounded by the algorithmic bias results. The systems of AI trained on materials of mainly English-linguistic and Western origins systematically perform poorly when applied to the materials of non-Western culture. It is not an isolated case that African-language materials have an accuracy rate of 31-42% less than the ones of other languages as reported by Oluwole et al. (2021); it is a systematic disadvantage of the scholars, students, and researchers who use these materials. To deal with this particular issue, it is necessary to implement both technical interventions, such as the creation of multilingual, multi-cultural training datasets, as well as institutional ones, in which the key library institutions should invest in the creation of equitable AI-based cataloguing.

5.4 Workforce Transformation

The AI adoption in terms of workforce is controversial and complicated. The fact that 48% of the librarians who do cataloguing are worried about job displacement due to AI development (Park and Tosaka, 2022) is a valid professional anxiety rooted in the historical tendencies of automating information labour. Nonetheless, the sources covered throughout this paper point to the possibility that the immediate effect of AI will be more of a professional change than a mass displacement. The increasing complexity of the digital collections, the widening of metadata management processes to feature research data sets and born-digital materials as well as the necessity of AI systems monitoring all place pressure on the need to have cataloguing skills that may not vanish in the near future.

The most important obstacle is the 66 percent gap in competencies found by LISEN (2023) - the percentage of cataloguers who are not sure about how to handle AI cataloguing systems. To close this gap, it is necessary to invest in the professional development process over the long term, and reorganize the LIS graduate education strategy by focusing on data literacy, AI assessment, and computational cataloguing skills. The recommendations of the curriculum review presented by Bawden and Robinson (2023) can offer a helpful outline of this reorientation, although it is going to need both the intake of the LIS school initiative and investment by the employer in the further education.

5.5 Theoretical Implications

The results of this review apply to theoretical models applied to explain the adoption of technology in academic libraries. The Technology Acceptance Model (TAM), used extensively to date in the research on AI cataloguing adoption, offers an incomplete but not exhaustive framework: perceived usefulness and ease of use are still relevant, but the evidence showed that the equity issues, ethical implications, and professional identity processes are also activated and cannot be well explained in the framework of TAM. A more long-standing theoretical framework, which combines technology acceptance with critical theories of professional practice, equity, and organizational change, should be used to inform the future research on AI adoption in the library environment.

6. Conclusion

6.1 Summary of Key Findings

The current paper has offered an in-depth evidence-based discussion of AI-based cataloguing and classification in academic libraries in the digital economy. The literature review based on the systematic review conducted in 2019-2025 creates five major findings. First, the AI-based cataloguing technologies have reached performance levels (8293% classification accuracy; 89% subject heading agreement) to be deployed in production in academic library cataloguing processes, and AI-assisted cataloguing can provide processing time savings of up to 60%. Second, the digital economy has increased AI cataloguing adoption many times over, and the share of ARL libraries using AI cataloguing tools has increased between 2019 and 2024, going up to 54% to cope with exponentially growing digital collections and to compete with commercial discovery tools. Third, major obstacles such as historical data quality issues, predisposition of algorithms towards non-Western content, human resource skills, and severe financial and infrastructure limitations in libraries of developing nations limit the fairness and efficiency of AI cataloguing implementation as it is being implemented significantly. Fourth, a human and AI collaborative model, where AI is used to perform automatic cataloguing operations and human cataloguers oversee and deal with high-value materials, is the most empirically validated implementation mode that allows balancing efficiency with quality. Fifth, the move to the linked data structures (BIBFRAME), along with the long-term cataloguing efficacy, is not only a strategic requirement of AI participation in the larger digital knowledge ecosystem, but it is also a crucial enabler of library participation in the larger digital knowledge ecosystem.

6.2 Limitations

This research paper is limited in a number of ways that would guide its findings interpretation. The systematic review approach is rigorous in terms of inclusion / exclusions criteria, but is constrained by the accessibility and availability of published study: libraries in developing countries are underrepresented in the library science literature of the international literature, and the results of libraries well-resourced in North America and Europe cannot be blindly applied to other settings. The swiftly changing character of AI technology implies that specific performance

measures provided will be overtaken comparatively soon; the directional results and strategic models are more stable than the individual ones. Lastly, longitudinal research is not explored in the existing literature, so the long-term effects of AI cataloguing on the quality of catalogues, the level of user satisfaction, and the group of professionals are not revealed yet.

6.3 Recommendations for Future Research

Further studies are advised to focus on: (1) longitudinal studies of quality and user discovery success of AI-based cataloguing over time in libraries that have applied AI cataloguing, to determine whether this efficiency improvement is sustained and by what means; (2) the empirical studies of AI cataloguing adoption and use in academic libraries in sub-Saharan Africa, southeast Asia, and Latin America, to fill the geographic evidence gap and inform equitable implementation strategies; (3) the possibility of developing and testing multilingual, multi-cultural training datasets to AI cataloguing systems, to address the systematic

The online economy will keep on developing, introducing new information formats, new demands of users, and new possibilities of AI to the academic library cataloguing. Those libraries that make a strategic investment in AI-based cataloguing today, without sacrificing on professional values, equity, and quality, will be best able to actualize its knowledge management mission in the twenty-first century information ecosystem.

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MULTIFUNCTIONAL ROLES OF *TRICHODERMA* SPP. IN STRAWBERRY AGROECOSYSTEMS: MECHANISMS, PLANT–MICROBE INTERACTIONS AND IMPLICATIONS FOR SUSTAINABLE DISEASE MANAGEMENT

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ABSTRACT

Strawberry (*Fragaria* × *ananassa*) production systems represent sensitive agroecosystems in terms of soil health and microbial balance, where soilborne pathogens—including *Fusarium oxysporum*, *Rhizoctonia solani*, *Macrophomina phaseolina*, and *Phytophthora* spp.—damage roots and vascular tissues, leading to significant yield losses. While chemical fungicides have been widely used for disease control, their long-term application poses sustainability challenges, including resistance development and environmental contamination. In this context, *Trichoderma* species, owing to their antagonistic and ecological functions, have emerged as key components of sustainable strawberry production systems. This study evaluates the roles of *Trichoderma* species in strawberry agroecosystems, focusing on their biocontrol mechanisms, plant–microorganism interactions, microbiome modulation, and contributions to agroecosystem resilience. Classical antagonistic mechanisms—such as hyperparasitism, antibiosis, and niche competition—are examined alongside associated hydrolytic enzymes (chitinases, β-1,3-glucanases, proteases), secondary metabolites, and volatile organic compounds (VOCs). Pathogen suppression processes are further discussed at the molecular level, including gene expression patterns and signal transduction pathways involved in antagonistic interactions. In addition, the symbiotic associations established between *Trichoderma* and strawberry plants, particularly rhizosphere colonization dynamics, are linked to enhanced nutrient uptake efficiency and improved plant growth performance. The activation of induced systemic resistance (ISR) mechanisms contributes to increased stress tolerance and strengthens overall agroecosystem resilience. Beyond biotic stress mitigation, the role of *Trichoderma* species in enhancing plant tolerance to abiotic stress factors—such as drought, salinity, and temperature fluctuations—is examined within the broader framework of ecosystem stability. Furthermore, ecosystem-level impacts are assessed from a holistic perspective, including shifts in the structural and functional composition of the rhizosphere microbiome, the formation of beneficial microbial consortia, and improvements in soil health. Practical application strategies—such as seedling root dipping treatments, soil inoculation, combinations with organic amendments, and advanced formulation technologies—are evaluated within integrated disease management systems. Their potential to reduce chemical inputs and support organic production systems is discussed in the context of sustainable agricultural policies. In conclusion, *Trichoderma* species in strawberry agroecosystems exhibit multifunctional roles that extend beyond pathogen suppression, encompassing the holistic support of plant health, stress tolerance, and microbial balance. Future research integrating omics technologies, microbiome

analyses, and climate change scenarios will contribute to a deeper understanding of this multifunctional framework and facilitate the development of sustainable disease management strategies.

Keywords: Biological control*, Fragaria* × *ananassa,* Fusarium wilt*,* Hyperparasitism, Root rot

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ÇİLEK AGROEKOSİSTEMLERİNDE *TRİCHODERMA* TÜRLERİNİN ÇOK YÖNLÜ İŞLEVLERİ: ETKİ MEKANİZMALARI, BİTKİ–MİKROORGANİZMA ETKİLEŞİMLERİ VE SÜRDÜRÜLEBİLİR HASTALIK YÖNETİMİ AÇISINDAN ÖNEMİ

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ÖZET

Çilek (*Fragaria* × *ananassa*) üretim sistemleri, toprak sağlığı ve mikrobiyal denge açısından hassas tarımsal ekosistemler olup, bu sistemlerde *Fusarium oxysporum, Rhizoctonia solani, Macrophomina phaseolina* ve *Phytophthora* türleri gibi topraktan bulaşan patojenler kökleri ve damar dokularını tahrip ederek önemli verim kayıplarına yol açmaktadır. Hastalık kontrolü için kimyasal fungisitler yaygın olarak kullanılsa da, bunların uzun süreli kullanımı direnç gelişimi ve çevre kirliliği gibi sürdürülebilirlik sorunlarına yol açmaktadır. Bu bağlamda, *Trichoderma* türleri, antagonistik ve ekolojik işlevleri sayesinde, sürdürülebilir çilek üretim sistemlerinin kilit bileşenleri olarak öne çıkmıştır. Bu çalışma, biyolojik mücadele mekanizmalarına, bitki-mikroorganizma etkileşimlerine, mikrobiyom modülasyonuna ve agroekosistem direncine katkılarına odaklanarak, çilek agroekosistemlerinde *Trichoderma* türlerinin rollerini değerlendirmektedir. Hiperparazitizm, antibiyoz ve niş rekabeti gibi klasik antagonistik mekanizmalar, ilişkili hidrolitik enzimler (kitinazlar, β-1,3-glukanazlar, proteazlar), ikincil metabolitler ve uçucu organik bileşikler (VOC'ler) ile birlikte incelenmektedir. Patojen bastırma süreçleri, antagonistik etkileşimlerde rol oynayan gen ekspresyon modelleri ve sinyal iletim yolları da dahil olmak üzere moleküler düzeyde daha ayrıntılı olarak tartışılmaktadır. Buna ek olarak, *Trichoderma* ve çilek bitkileri arasında kurulan simbiyotik ilişkiler, özellikle de rizosfer kolonizasyon dinamikleri, besin alım verimliliğinin artması ve bitki büyüme performansının iyileşmesi ile bağlantılıdır. İndüklenmiş sistemik direnç (ISR) mekanizmalarının aktivasyonu, stres toleransının artmasına katkıda bulunur ve genel tarımsal ekosistem direncini güçlendirir. Biyotik stresin hafifletilmesinin ötesinde, *Trichoderma* türlerinin kuraklık, tuzluluk ve sıcaklık dalgalanmaları gibi abiyotik stres faktörlerine karşı bitki toleransını artırmadaki rolü, ekosistem istikrarının daha geniş çerçevesi içinde incelenmektedir. Ayrıca, rizosfer mikrobiyomunun yapısal ve işlevsel bileşimindeki değişiklikler, faydalı mikrobiyal konsorsiyumların oluşumu ve toprak

sağlığındaki iyileşmeler dahil olmak üzere, ekosistem düzeyindeki etkiler bütünsel bir bakış açısıyla değerlendirilmektedir. Fide kök daldırma işlemleri, toprak aşılaması, organik gübrelerle kombinasyonlar ve gelişmiş formülasyon teknolojileri gibi pratik uygulama stratejileri, entegre hastalık yönetim sistemleri içinde değerlendirilmektedir. Kimyasal girdileri azaltma ve organik üretim sistemlerini destekleme potansiyelleri, sürdürülebilir tarım politikaları bağlamında tartışılmaktadır. Sonuç olarak, çilek agroekosistemlerindeki *Trichoderma* türleri, patojenlerin bastırılmasının ötesine geçen, bitki sağlığı, stres toleransı ve mikrobiyal dengenin bütünsel desteğini kapsayan çok işlevli roller sergilemektedir. Omik teknolojileri, mikrobiyom analizleri ve iklim değişikliği senaryolarını entegre eden gelecekteki araştırmalar, bu çok işlevli çerçevenin daha derinlemesine anlaşılmasına katkıda bulunacak ve sürdürülebilir hastalık yönetimi stratejilerinin geliştirilmesini kolaylaştıracaktır.

Anahtar Kelimeler: Biyolojik mücadele, *Fragaria* × *ananassa*, Fusarium solgunluğu, Hiperparazitizm, Kök çürüklüğü

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1. Giriş

Çilek (*Fragaria* × *ananassa* Duch.), yüksek katma değerli üretim yapısı, kısa yetiştirme döngüsü ve taze tüketim başta olmak üzere işleme sanayisindeki geniş kullanım alanı nedeniyle dünya genelinde stratejik bir meyve türüdür. Bununla birlikte çilek üretimi, yoğun tarım uygulamaları, tekrarlı dikim sistemleri ve yüksek nem koşulları nedeniyle özellikle toprak kökenli patojenlerin baskısı altındadır. *Fusarium oxysporum* (solgunluk), *Rhizoctonia solani* (kök çürüklüğü), *Macrophomina phaseolina* (kömür çürüklüğü) ve *Phytophthora* spp. (kök ve kök boğaz çürüklüğü) gibi patojenler, kök sistemini ve iletim demetlerini tahrip ederek bitki gelişimini ciddi şekilde sınırlandırmakta, sonuçta verim ve kalite kayıplarına neden olmaktadır (Maas, 1998). Ayrıca, *Botrytis cinerea* (gri küf) ve *Colletotrichum* spp. (antraknoz) gibi hava kökenli patojenler de özellikle meyve döneminde önemli ekonomik kayıplara yol açmaktadır (Mirmajlessi vd., 2015; Drobek vd., 2021; Nakielska vd., 2024).

Bu patojenlerle mücadelede uzun yıllardır kimyasal fungisitler temel araç olarak kullanılmıştır (Fravel, 2005). Ancak, fungisitlere karşı direnç gelişimi, kalıntı problemleri, çevresel kirlilik ve insan sağlığına yönelik riskler, sürdürülebilir üretim sistemleri açısından ciddi sınırlamalar oluşturmaktadır (Glare vd., 2012). Bu nedenle, biyolojik mücadele ajanlarına olan ilgi son yıllarda belirgin şekilde artmıştır. Bu bağlamda, filamentöz funguslar arasında yer alan *Trichoderma* türleri, çok yönlü biyolojik işlevleri sayesinde en yaygın ve en etkili biyokontrol ajanları arasında kabul edilmektedir (Lamichhane vd., 2016; Köhl vd., 2019).

Günümüzde 200'den fazla *Trichoderma* türü tanımlanmış olup, bunların önemli bir kısmı tarımsal biyokontrol ve bitki gelişim teşviki amacıyla kullanılmaktadır (Samuels, 2006). Ticari ve araştırma düzeyinde en yaygın kullanılan türler arasında *T. harzianum, T. asperellum, T. viride, T.*

atroviride ve *T. koningii* yer almaktadır (Druzhinina vd., 2011). Bu türler, farklı agroekosistemlerde geniş adaptasyon yetenekleri ve güçlü antagonistik aktiviteleri nedeniyle öne çıkmaktadır. Özellikle çilek üretim sistemlerinde *T. harzianum* ve *T. asperellum*, hem patojen baskılama hem de bitki büyümesini teşvik etme açısından en yaygın kullanılan türlerdir (Błaszczyk vd., 2014; Woo vd., 2014). Literatürde, *T. harzianum*'un çilekte *Rhizoctonia solani* ve *Fusarium oxysporum*'a karşı yüksek düzeyde biyokontrol etkinliği gösterdiği; *T. asperellum*'un ise özellikle *Phytophthora cactorum* kaynaklı kök ve kök boğaz çürüklüğüne karşı etkili olduğu bildirilmiştir (Porras vd., 2007; Ahmed vd., 2017). Benzer şekilde, *T. viride*'nin *Macrophomina phaseolina* üzerinde baskılayıcı etkisi olduğu ve bitki kök gelişimini artırarak dolaylı koruma sağladığı ifade edilmektedir. Bu türlerin etkinliği yalnızca patojen baskılama ile sınırlı olmayıp, aynı zamanda bitki fizyolojisini düzenleyici etkilerle de ilişkilidir (Awais vd., 2021; Liu vd., 2024).

Trichoderma spp.'nin çilek agroekosistemlerindeki başarısı, sadece klasik antagonistik mekanizmalarla açıklanamaz. Bu organizmalar, rizosferde hızlı kolonizasyon yetenekleri sayesinde mikrobiyal dengeyi yeniden şekillendirmekte, bitki kökleriyle etkileşime girerek besin alımını artırmakta ve bitki savunma sistemlerini aktive etmektedir. Ayrıca, sekonder metabolitler ve uçucu organik bileşikler (VOCs) aracılığıyla hem doğrudan hem de dolaylı patojen baskılama mekanizmaları geliştirmektedirler (Harman vd., 2004; Vinale vd., 2008a). Bu çok katmanlı etki mekanizmaları, *Trichoderma* türlerini yalnızca bir biyokontrol ajanı değil, aynı zamanda agroekosistem mühendisliği açısından kritik bir biyolojik araç haline getirmektedir. Sonuç olarak, çilek üretim sistemlerinde sürdürülebilir hastalık yönetimi stratejilerinin geliştirilmesinde *Trichoderma* türleri, geniş tür çeşitliliği, çok yönlü etki mekanizmaları ve çevre dostu özellikleri ile öne çıkmakta; hem patojen baskılama hem de bitki sağlığının bütüncül iyileştirilmesi açısından vazgeçilmez bir bileşen olarak değerlendirilmektedir (Lombardi vd., 2020; Yao vd., 2023).

2. *Trichoderma* Türlerinin Biyokontrol Mekanizmaları

2.1. Mikoparazitizm (Hiperparazitizm)

Trichoderma türlerinin en karakteristik biyokontrol mekanizmalarından biri mikoparazitizmdir. Bu süreçte *Trichoderma*, hedef patojen fungusun hiflerini tanır, onlara yönelir ve doğrudan fiziksel temas kurarak parazitlemeye başlar. Bu olay, basit bir temas sürecinden ziyade oldukça karmaşık ve düzenlenmiş bir biyolojik etkileşimdir. İlk aşamada *Trichoderma*, patojen fungus tarafından salgılanan kimyasal sinyalleri algılar (kemotaksi) ve büyüme yönünü bu sinyallere göre belirler. Ardından patojen hifine temas eden *Trichoderma* hifleri, etmeni sararak "koiling" adı verilen spiral yapı oluşturur. Bu yapı, patojenin yüzeyine güçlü bir şekilde tutunmayı sağlar (Howell, 2003). Temasın ardından *Trichoderma*, patojen hücre duvarını parçalamaya yönelik litik enzimler salgılar. Bu enzimler arasında özellikle kitinazlar, β-1,3-glukanazlar ve proteazlar kritik rol oynar. Kitinazlar, fungal hücre duvarının ana bileşenlerinden biri olan kitini parçalayarak yapısal bütünlüğü bozar. β-1,3-glukanazlar, glukan matriksini hidrolize ederken, proteazlar hücre duvarı proteinlerini degrade eder. Bu enzimatik saldırı sonucunda patojen hücre duvarı zayıflar, geçirgenliği artar ve hücre içeriği dış ortama sızarak hücre ölümü gerçekleşir

(Benítez vd., 2004). Moleküler düzeyde, bu süreç belirli genlerin aktivasyonu ile kontrol edilir. *Trichoderma*'da ech42 (endochitinaz), nag1 (N-asetilglukozaminidaz) ve prb1 (proteaz) gibi genlerin ekspresyonu, mikoparazitizm sırasında belirgin şekilde artmaktadır (Zeilinger & Omann, 2007). Çilek agroekosistemlerinde mikoparazitizm özellikle *Rhizoctonia solani* ve *Fusarium oxysporum* gibi toprak kökenli patojenlerin kontrolünde kritik öneme sahiptir. Bu patojenler kök yüzeyinde ve toprakta aktif olarak bulunduğundan, *Trichoderma*'nın doğrudan temas yoluyla etki göstermesi oldukça avantajlıdır. Bu nedenle mikoparazitizm, *Trichoderma*'nın biyokontrol kapasitesinin temel taşlarından biri olarak kabul edilmektedir (Vinale vd., 2008a; Kubicek vd., 2011).

2.2. Antibiyozis ve Sekonder Metabolitler

Antibiyozis, *Trichoderma* türlerinin patojen mikroorganizmaları baskılamak için biyokimyasal bileşikler üretmesine dayanan önemli bir mekanizmadır. Bu süreçte *Trichoderma*, çevresine antifungal, antibakteriyel ve bazen antiviral etkiye sahip sekonder metabolitler salgılar. Bu metabolitler, patojenlerin hücre zarını bozabilir, metabolik faaliyetlerini inhibe edebilir veya spor çimlenmesini engelleyebilir (Elad, 2000). *Trichoderma* türleri tarafından üretilen başlıca antifungal bileşikler arasında gliotoksin, viridin, trichodermin, peptaiboller ve harzianik asit yer almaktadır. Örneğin gliotoksin, patojen hücrelerde oksidatif stres oluşturarak hücresel fonksiyonları bozar. Peptaiboller ise hücre zarına entegre olarak iyon dengesini bozmakta ve hücre ölümüne yol açmaktadır. Trichodermin gibi bazı metabolitler, protein sentezini inhibe ederek patojen büyümesini durdurur (Viterbo vd., 2007). Bunun yanı sıra, *Trichoderma* spp. uçucu organik bileşikler (VOCs) de üretmektedir. Bu bileşikler, doğrudan temas gerektirmeden patojenler üzerinde baskılayıcı etki oluşturur. 6-pentil-α-piron (6-PP) gibi VOC'ler, hem antifungal etki gösterir hem de bitki büyümesini teşvik edici özelliklere sahiptir. VOC'lerin bu çift yönlü etkisi, *Trichoderma*'nın agroekosistemlerdeki önemini daha da artırmaktadır (Reino vd., 2008). Çilek üretiminde antibiyozis mekanizması özellikle *Botrytis cinerea* ve *Colletotrichum* spp. gibi hava kökenli patojenlerin kontrolünde önemlidir. Bu patojenlerle doğrudan temas her zaman mümkün olmadığından, difüzyon yoluyla etki eden antifungal bileşikler önemli avantaj sağlar. Ayrıca antibiyozis, mikoparazitizm ve rekabet mekanizmalarıyla birlikte sinerjik olarak çalışarak daha güçlü bir biyokontrol etkisi oluşturur. Kısaca, sekonder metabolit üretimi, *Trichoderma*'nın biyokontrol etkinliğini artıran ve geniş spektrumlu patojen baskılama sağlayan kritik bir mekanizmadır (Vinale vd., 2008b).

2.3. Rekabet (Niş ve Besin Rekabeti)

Rekabet, *Trichoderma* türlerinin rizosferde patojenlerle aynı kaynakları kullanarak onların gelişimini sınırladığı temel biyokontrol mekanizmalarından biridir. Bu mekanizma, doğrudan patojen öldürmeye dayanmaz; bunun yerine patojenin yaşam alanını ve besin kaynaklarını kısıtlayarak dolaylı bir baskılama sağlar. *Trichoderma* spp., hızlı büyüme oranı, yüksek spor üretim kapasitesi ve güçlü rizosfer kolonizasyon yeteneği sayesinde bu rekabette genellikle avantajlı konumdadır (Papavizas, 1985). *Trichoderma* türleri, özellikle karbon ve azot kaynaklarını etkin bir

şekilde kullanarak patojenlerin bu kaynaklara erişimini sınırlar. Ayrıca siderofor üretimi yoluyla demir gibi sınırlayıcı mikro elementleri bağlayarak patojenlerin büyümesini engeller (Benítez vd., 2004). Demir, birçok patojen için kritik bir element olduğundan, siderofor aracılı rekabet önemli bir baskılama mekanizmasıdır. Rizosfer kolonizasyonu, rekabet mekanizmasının en önemli bileşenlerinden biridir. *Trichoderma*, bitki kök yüzeyine hızla yerleşerek burada biyofilm benzeri yapılar oluşturur. Bu durum, patojenlerin kök yüzeyine tutunmasını fiziksel olarak engeller (Harman vd., 2004). Aynı zamanda kök eksudatlarını hızla tüketerek patojenlerin besin kaynağını azaltır. Bu özellik, özellikle çilek gibi yüzeysel kök sistemine sahip bitkilerde büyük avantaj sağlar (Mendes vd., 2011).

Çilek agroekosistemlerinde rekabet mekanizması, *Fusarium oxysporum* ve *Macrophomina phaseolina* gibi toprakta uzun süre canlı kalabilen patojenlerin kontrolünde kritik rol oynar. Bu patojenler sklerot veya klamidiospor gibi dayanıklı yapılar oluşturduğundan, doğrudan öldürülmeleri zor olabilir (Ahmed vd., 2017). Ancak *Trichoderma*'nın rekabetçi üstünlüğü, bu patojenlerin aktif hale geçmesini ve enfeksiyon oluşturmasını engelleyebilir. Ayrıca rekabet mekanizması, mikrobiyom düzeyinde de etkili olup faydalı mikroorganizmaların gelişimini destekleyerek patojen baskısını artırır. Bu yönüyle *Trichoderma*, sadece bireysel bir biyokontrol ajanı değil, aynı zamanda rizosfer ekosistemini yeniden şekillendiren bir "mikrobiyal düzenleyici" olarak işlev görmektedir. Sonuç olarak, niş ve besin rekabeti, *Trichoderma*'nın sürdürülebilir biyokontrol stratejilerindeki başarısının temel bileşenlerinden biri olup, diğer mekanizmalarla birlikte çalışarak uzun süreli ve stabil bir hastalık baskılama sağlar (Liu vd., 2024; Yao vd., 2023).

3. Bitki–Trichoderma Etkileşimleri ve Moleküler Mekanizmalar

Trichoderma türleri ile bitki arasındaki etkileşim, klasik patojen–konukçu ilişkisinden farklı olarak çoğunlukla mutualistik veya yarı simbiyotik bir yapı sergiler. Bu etkileşim, kök yüzeyinde başlayan ve rizosfer boyunca devam eden çok katmanlı bir iletişim ağına dayanır (Harman vd., 2004; Hermosa vd., 2012). *Trichoderma*, bitki kök eksudatlarında bulunan şekerler, amino asitler ve fenolik bileşikler tarafından çekilerek kök yüzeyine yönelir ve burada hızlı bir kolonizasyon gerçekleştirir. Bu süreçte hem bitki hem de mikroorganizma karşılıklı sinyaller üretir; bu sinyaller, bitkinin savunma sistemlerinin aşırı aktivasyonunu önlerken aynı zamanda kontrollü bir bağışıklık yanıtı oluşturulmasını sağlar (Mukherjee vd., 2013; Guzmán-Guzmán vd., 2019).

Moleküler düzeyde bu etkileşim, bitki tarafından "yararlı mikroorganizma" olarak tanınmayı sağlayan spesifik moleküler desenler (MAMPs/Microbe-Associated Molecular Patterns) ile düzenlenir (Brotman vd., 2013; Contreras-Cornejo vd., 2009). *Trichoderma* kaynaklı elisitör proteinler (örneğin Sm1, Epl1) bitkide düşük seviyeli bir savunma yanıtı başlatır ve bu durum bitkinin daha sonraki patojen saldırılarına karşı "hazırlıklı" hale gelmesini sağlar (Priming etkisi). Ayrıca bu etkileşim sırasında bitkide kök mimarisi değişmekte, lateral kök oluşumu artmakta ve besin alım kapasitesi yükselmektedir (Shoresh vd., 2010; Pieterse vd., 2014).

3.1. Sinyal İletim Yolları

Trichoderma ile bitki arasındaki etkileşim, karmaşık sinyal iletim ağları aracılığıyla düzenlenir ve bu süreçte bitki hormonları merkezi rol oynar. Özellikle jasmonik asit (JA), etilen (ET) ve salisilik asit (SA) sinyal yolları, bitkinin savunma yanıtlarının şekillenmesinde kritik öneme sahiptir. *Trichoderma* spp. genellikle JA ve ET bağımlı savunma yollarını aktive ederek nekrotrof patojenlere karşı direnç oluşturur (Shoresh & Harman, 2008). Buna karşılık, SA yolu daha çok biyotrof patojenlere karşı etkili olmakla birlikte, bu yollar arasında çapraz koruma (Cross-protection) gerçekleşerek dengeli bir savunma yanıtı oluşturulur. Bu süreçte *Trichoderma*, bitkide hormon benzeri bileşikler veya sinyal modülatörleri üretir (Shoresh & Harman, 2008; Tucci vd., 2011). Örneğin bazı *Trichoderma* izolatları, oksin benzeri bileşikler salgılayarak kök gelişimini teşvik ederken, aynı zamanda savunma ile ilişkili genlerin ekspresyonunu düzenleyebilir. Ayrıca MAP kinaz (MAPK) sinyal yolları, kalsiyum bağımlı sinyal yolları ve reaktif oksijen türleri (ROS) bu etkileşimde önemli rol oynar. ROS üretimi, kontrollü seviyelerde olduğunda hem savunma yanıtlarını aktive eder hem de hücresel sinyal iletiminde görev alır (Nawrocka & Małolepsza, 2013). Çilek bitkisinde yapılan çalışmalar, *Trichoderma* uygulamalarının JA/ET yolaklarını aktive ederek özellikle *Botrytis cinerea* ve *Colletotrichum* spp. gibi patojenlere karşı direnç oluşturduğunu göstermektedir. Bu nedenle sinyal iletim mekanizmaları, *Trichoderma*'nın bitki savunma sistemlerini nasıl yönlendirdiğini anlamak açısından kritik bir araştırma alanıdır (Pieterse vd., 2014).

3.2. Gen Ekspresyonu ve ISR (Induced Systemic Resistance)

Trichoderma spp., bitkide indüklenmiş sistemik direnç (ISR) mekanizmasını tetikleyerek geniş spektrumlu bir savunma yanıtı oluşturur. ISR, patojen varlığı olmaksızın bitkinin savunma sisteminin "hazırlık durumuna" geçirilmesi olarak tanımlanabilir. Bu süreçte bitki, patojen saldırısı gerçekleştiğinde daha hızlı ve güçlü bir yanıt verebilecek şekilde metabolik olarak programlanır (Shoresh vd., 2010). Moleküler düzeyde ISR, çeşitli savunma genlerinin aktivasyonu ile ilişkilidir. Bu genler arasında PR (Pathogenesis-related) proteinleri, kitinazlar, glukanazlar ve fenilpropanoid yolak enzimleri yer almaktadır (Hermosa vd., 2012). Özellikle PR1, PR2 ve PR5 gibi genlerin ekspresyonu, *Trichoderma* uygulamalarından sonra artış göstermektedir. Ayrıca lignin ve fitoaleksin sentezinde görev alan genlerin aktivasyonu, hücre duvarının güçlendirilmesine ve patojen girişinin engellenmesine katkı sağlar (Pieterse vd., 2014; Yao vd., 2023).

ISR'nin önemli özelliklerinden biri, enerji açısından ekonomik olmasıdır. Bitki sürekli olarak yüksek düzeyde savunma yanıtı üretmek yerine, "priming" sayesinde gerektiğinde hızlı tepki verecek şekilde hazırlanır. Bu durum, büyüme ve savunma arasındaki dengeyi korur. Çilek bitkisinde yapılan çalışmalar, *Trichoderma* uygulamalarının hem kök hem de yaprak düzeyinde savunma genlerini aktive ederek sistemik bir koruma sağladığını göstermektedir. *Trichoderma*'nın ISR mekanizması, yalnızca lokal değil tüm bitkiyi kapsayan bir savunma stratejisi sunarak, sürdürülebilir hastalık yönetiminde güçlü bir biyolojik araç olarak öne çıkmaktadır.

4. Çilekte Hastalık Yönetiminde *Trichoderma*

Çilek üretim sistemlerinde hastalık yönetimi, özellikle toprak kökenli patojenlerin sürekliliği ve çevresel koşulların hastalık gelişimini teşvik etmesi nedeniyle oldukça karmaşık bir süreçtir. Bu bağlamda *Trichoderma* türleri, hem doğrudan patojen baskılama hem de bitki savunma mekanizmalarını aktive etme kapasiteleri sayesinde entegre hastalık yönetimi (IPM) programlarının önemli bir bileşeni haline gelmiştir (Maas, 1998; Mirmajlessi vd., 2015). Çilekte yaygın olarak kullanılan *Trichoderma* harzianum, *Trichoderma* asperellum ve *Trichoderma* viride gibi türler, farklı patojenlere karşı geniş spektrumlu etki göstermektedir (Awais vd., 2021; Drobek vd., 2021).

Toprak kökenli patojenler arasında yer alan *Fusarium oxysporum*, çilekte solgunluk hastalığının başlıca etmenlerinden biridir ve vasküler dokuları tahrip ederek bitkinin su iletimini engeller. Bu patojene karşı *T. harzianum* uygulamalarının, hem patojen yoğunluğunu azalttığı hem de bitkide savunma genlerini aktive ederek hastalık şiddetini önemli ölçüde düşürdüğü bildirilmektedir (Porras vd., 2007). Benzer şekilde, *Rhizoctonia solani* kaynaklı kök çürüklüğüne karşı *Trichoderma* uygulamaları, rizosferde hızlı kolonizasyon ve mikoparazitizm yoluyla etkili bir baskılama sağlamaktadır. Bu patojenin özellikle fide döneminde oluşturduğu kayıplar göz önüne alındığında, fide kök daldırma şeklindeki *Trichoderma* uygulamaları oldukça kritik bir önleyici strateji olarak öne çıkmaktadır (Ahmed vd., 2017). Çilekte önemli bir diğer patojen olan *Phytophthora cactorum*, kök ve kök boğaz çürüklüğüne neden olarak ani bitki ölümlerine yol açabilmektedir. *T. asperellum*'un bu patojene karşı hem doğrudan antagonistik etki gösterdiği hem de bitkide indüklenmiş sistemik direnç (ISR) mekanizmasını aktive ederek dolaylı koruma sağladığı rapor edilmiştir. Ayrıca *Macrophomina phaseolina* gibi stres koşullarında daha agresif hale gelen patojenlere karşı *Trichoderma* uygulamalarının, hem patojen gelişimini sınırladığı hem de bitkinin stres toleransını artırarak hastalık etkisini azalttığı görülmektedir (Nelson vd., 2021; Sharma vd., 2022; Evenhuis vd., 2024).

Hava kökenli patojenler açısından değerlendirildiğinde, *Botrytis cinerea* ve *Colletotrichum* spp. çilek meyvelerinde ciddi kalite kayıplarına neden olmaktadır (Card vd., 2009; Barakat & Al-Masri, 2017). Bu patojenlere karşı *Trichoderma* spp.'nin ürettiği uçucu organik bileşikler (VOCs) ve antifungal metabolitler, doğrudan temas gerektirmeden etkili bir baskılama sağlayabilmektedir. Özellikle çiçeklenme ve meyve oluşumu dönemlerinde yapılan yaprak veya yüzey uygulamaları, enfeksiyon riskini azaltmada önemli rol oynar (Lombardi vd., 2020; Schierling vd., 2024).

Uygulama stratejileri açısından *Trichoderma*, fide kök daldırma, toprak inokulasyonu, organik materyallerle kombinasyon ve damla sulama sistemleri ile verilerek etkili bir şekilde kullanılabilmektedir (Fravel, 2005; Woo vd., 2014). Bu uygulamaların başarısı; kullanılan izolatın adaptasyon yeteneği, çevresel koşullar ve uygulama zamanlaması gibi faktörlere bağlıdır (van Lenteren vd., 2018). *Trichoderma* türleri çilekte hastalık yönetiminde sadece alternatif bir yöntem değil, aynı zamanda kimyasal girdilerin azaltılmasını sağlayan sürdürülebilir ve çevre dostu bir strateji olarak değerlendirilmektedir (Köhl vd., 2019).

5. Uygulama Stratejileri ve Entegre Hastalık Yönetimi

Çilek agroekosistemlerinde *Trichoderma* türlerinin etkinliği, yalnızca biyolojik özelliklerine değil, aynı zamanda doğru uygulama stratejilerinin seçimine ve entegre hastalık yönetimi (IPM) sistemleriyle uyumlu şekilde kullanılmasına bağlıdır (Ahmed vd., 2017). Bu nedenle *Trichoderma* uygulamaları, bitki gelişim dönemleri, patojen baskısı ve çevresel koşullar dikkate alınarak planlanmalıdır (Awais vd., 2021). En yaygın uygulama yöntemlerinden biri fide kök daldırma işlemidir. Bu yöntemde, çilek fideleri dikim öncesinde *Trichoderma* spor süspansiyonu içerisine daldırılarak kök yüzeyinde erken kolonizasyon sağlanır. Bu erken kolonizasyon, özellikle *Rhizoctonia solani* ve *Fusarium oxysporum* gibi toprak kökenli patojenlerin enfeksiyonunu önlemede kritik rol oynar (Liu vd., 2024).

Toprak inokulasyonu, *Trichoderma*'nın rizosferde kalıcı bir popülasyon oluşturmasını sağlayan bir diğer önemli uygulama yöntemidir. Bu uygulama, granül formülasyonlar veya sıvı preparatlar aracılığıyla gerçekleştirilebilir (Mendes vd., 2011). Özellikle organik madde açısından zengin topraklarda *Trichoderma*'nın kolonizasyon başarısı artmakta ve biyokontrol etkinliği daha stabil hale gelmektedir (Berendsen vd., 2012). Bu bağlamda, kompost, vermikompost ve biyokömür gibi organik materyallerle birlikte yapılan uygulamalar, hem mikrobiyal aktiviteyi artırmakta hem de *Trichoderma*'nın rizosferdeki rekabet gücünü desteklemektedir (Compant vd., 2019; Drobek vd., 2021).

Damla sulama sistemleri ile uygulama, modern çilek üretiminde yaygın olarak kullanılan bir yöntemdir. Bu teknik, *Trichoderma* inokulumunun kök bölgesine homojen bir şekilde dağıtılmasını sağlar ve özellikle büyük ölçekli üretim alanlarında pratik bir çözüm sunar. Ayrıca yaprak uygulamaları, özellikle Botrytis cinerea gibi hava kökenli patojenlere karşı koruyucu bir strateji olarak değerlendirilmektedir (Porras vd., 2007; Card vd., 2009). Bu uygulamalarda, *Trichoderma*'nın ürettiği uçucu organik bileşikler ve antifungal metabolitler, patojen sporlarının çimlenmesini ve yüzey kolonizasyonunu engelleyebilir (Barakat & Al-Masri, 2017; Liu vd., 2024).

Entegre hastalık yönetimi kapsamında *Trichoderma* uygulamaları, kimyasal fungisitler, kültürel önlemler ve dayanıklı çeşit kullanımı ile birlikte değerlendirilmelidir. Düşük dozda veya hedefe yönelik fungisit uygulamaları ile *Trichoderma* kombinasyonu, hem hastalık kontrolünü artırabilir hem de kimyasal kullanımını azaltabilir (Fravel, 2005). Ancak burada dikkat edilmesi gereken önemli bir nokta, kullanılan fungisitlerin *Trichoderma*'ya karşı toksik etkisinin düşük olmasıdır. Aksi takdirde biyolojik ajanların etkinliği azalabilir (Glare vd., 2012). Ayrıca, yerel koşullara adapte olmuş *Trichoderma* izolatlarının kullanılması, uygulama başarısını önemli ölçüde artırmaktadır. İzolat seçimi, sıcaklık, pH ve toprak yapısı gibi çevresel faktörlere uygunluk açısından kritik bir parametredir (Lamichhane vd., 2016). Son yıllarda geliştirilen gelişmiş formülasyon teknolojileri (mikrokapsülleme, taşıyıcı bazlı preparatlar) ise *Trichoderma*'nın raf ömrünü uzatmakta ve tarla koşullarındaki stabilitesini artırmaktadır (Köhl vd., 2019).

Trichoderma türlerinin çilek üretiminde etkin bir şekilde kullanılabilmesi için uygun uygulama yöntemlerinin seçilmesi, doğru zamanlama ve IPM stratejileri ile entegrasyonu büyük önem taşımaktadır (Woo vd., 2014; Yao vd., 2023). Bu bütüncül yaklaşım, hem hastalık baskısını azaltmakta hem de sürdürülebilir ve çevre dostu üretim sistemlerinin geliştirilmesine katkı sağlamaktadır (Nakielska vd., 2024).

6. Sınırlılıklar ve Gelecek Perspektifler

Trichoderma türleri çilek agroekosistemlerinde güçlü bir biyokontrol ve biyostimülant potansiyeli sunmasına rağmen, uygulama başarısı çeşitli biyotik ve abiyotik faktörlere bağlı olarak değişkenlik gösterebilmektedir. Bu değişkenliğin temel nedenlerinden biri izolat-spesifik etkinlik farklılıklarıdır. Aynı tür içerisinde yer alan farklı *Trichoderma* izolatları, patojen baskılama kapasitesi, rizosfer kolonizasyon yeteneği ve bitkiyle etkileşim düzeyi bakımından önemli farklılıklar sergileyebilir (Woo vd., 2014). Bu durum, "her koşulda etkili tek bir izolat" yaklaşımının sınırlı olduğunu ve hedef patojen ile çevresel koşullara özgü izolat seçiminin kritik olduğunu göstermektedir. Bir diğer önemli sınırlılık, çevresel koşullara bağlı performans değişkenliğidir. Toprak pH'ı, sıcaklık, nem, organik madde içeriği ve mikrobiyal rekabet gibi faktörler, *Trichoderma*'nın toprakta tutunma ve etkinlik düzeyini doğrudan etkilemektedir (Köhl vd., 2019). Özellikle tarla koşullarında, kontrollü laboratuvar veya sera sonuçlarının aynı düzeyde tekrar edilememesi, biyokontrol uygulamalarının yaygınlaşmasında önemli bir engel oluşturmaktadır. Ayrıca yoğun kimyasal kullanımının olduğu sistemlerde, fungisitlerin *Trichoderma* üzerindeki olumsuz etkileri de dikkate alınması gereken bir diğer faktördür (Liu vd., 2024).

Formülasyon ve raf ömrü sorunları da pratik uygulamalar açısından önemli sınırlılıklar arasında yer almaktadır. Canlı bir organizma olan *Trichoderma*'nın uzun süre etkinliğini koruyabilmesi, uygun taşıyıcı materyaller ve depolama koşullarına bağlıdır (Fravel, 2005). Uygun olmayan formülasyonlar, spor canlılığını azaltarak tarla performansını düşürebilir. Bu nedenle ticari ürünlerde stabilite, uygulama kolaylığı ve ekonomik sürdürülebilirlik önemli araştırma konuları olmaya devam etmektedir (Glare vd., 2012; van Lenteren vd., 2018).

Bununla birlikte, son yıllarda gelişen bilimsel yaklaşımlar *Trichoderma* araştırmalarına yeni bir boyut kazandırmıştır. Omik teknolojiler (genomik, transkriptomik, proteomik ve metabolomik), *Trichoderma*–bitki–patojen etkileşimlerinin moleküler temellerini daha ayrıntılı şekilde ortaya koyma imkânı sunmaktadır (Mukherjee vd., 2013). Bu yaklaşımlar sayesinde, biyokontrol etkinliğinden sorumlu genler, metabolik yollar ve sinyal iletim ağları daha net anlaşılmakta, böylece hedefe yönelik izolat geliştirme çalışmaları hız kazanmaktadır. Ayrıca, rizosfer mikrobiyomu ve mikrobiyal konsorsiyum yaklaşımları gelecekte önemli bir araştırma alanı olarak öne çıkmaktadır (Druzhinina vd., 2011; Kubicek vd., 2011). Tek bir biyokontrol ajanı yerine, *Trichoderma*'nın faydalı bakteri ve diğer mikroorganizmalarla birlikte kullanıldığı

konsorsiyumların daha stabil ve etkili sonuçlar verdiği görülmektedir. Bu durum, agroekosistemlerin daha bütüncül bir yaklaşımla ele alınmasını gerektirmektedir (Lorito vd., 2010).

İklim değişikliği de göz ardı edilmemesi gereken kritik bir faktördür. Artan sıcaklık, kuraklık ve ekstrem hava olayları hem patojen dinamiklerini hem de *Trichoderma*'nın etkinliğini etkileyebilir (Berendsen vd., 2012). Bu nedenle gelecekte yapılacak çalışmaların, iklim değişikliği senaryolarına uyumlu izolatların geliştirilmesine odaklanması gerekmektedir (Compant vd., 2019). Mevcut sınırlılıklara rağmen *Trichoderma* türleri sürdürülebilir tarımın en önemli biyolojik araçlarından biri olmaya devam etmektedir (Sharma vd., 2022). Gelecekte, disiplinler arası yaklaşımlar, ileri biyoteknolojik yöntemler ve saha-validasyon çalışmaları ile bu organizmaların potansiyelinin daha etkin bir şekilde kullanılması mümkün olacaktır (Evenhuis vd., 2024).

5. Sonuç

Trichoderma türleri, çilek agroekosistemlerinde yalnızca patojen baskılayan biyolojik ajanlar olarak değil, aynı zamanda bitki büyümesini teşvik eden, stres toleransını artıran ve rizosfer mikrobiyal dengesini düzenleyen çok işlevli mikroorganizmalar olarak öne çıkmaktadır. Bu derlemede ele alındığı üzere, mikoparazitizm, antibiyozis ve rekabet gibi klasik biyokontrol mekanizmalarının yanı sıra, bitki ile kurulan moleküler etkileşimler ve indüklenmiş sistemik direnç (ISR) gibi süreçler, *Trichoderma*'nın etkisini çok katmanlı bir yapıya dönüştürmektedir. Bu durum, çilek üretim sistemlerinde hem hastalık yönetimi hem de verim ve kalite artışı açısından önemli avantajlar sağlamaktadır.

Özellikle toprak kökenli patojenlerin yoğun olduğu üretim alanlarında *Trichoderma* uygulamaları, kimyasal fungisitlere olan bağımlılığı azaltarak çevre dostu ve sürdürülebilir üretim sistemlerinin geliştirilmesine katkı sunmaktadır. Bununla birlikte, uygulama başarısının izolat seçimi, çevresel koşullar ve uygun uygulama stratejilerine bağlı olduğu unutulmamalıdır. Bu nedenle, *Trichoderma*'nın etkin kullanımı, entegre hastalık yönetimi (IPM) çerçevesinde ele alınmalı ve diğer kültürel ve biyolojik yöntemlerle birlikte değerlendirilmelidir.

Gelecekte, omik teknolojiler, mikrobiyom analizleri ve gelişmiş formülasyon teknikleri ile *Trichoderma*'nın bitki–mikroorganizma etkileşimlerindeki rolü daha derinlemesine anlaşılacaktır. Bu gelişmeler, hedefe yönelik izolat geliştirilmesi ve saha koşullarında daha stabil uygulamaların yaygınlaşmasını sağlayacaktır. Sonuç olarak, *Trichoderma* türleri, çilek agroekosistemlerinde sürdürülebilir hastalık yönetimi ve üretim verimliliğinin artırılması açısından vazgeçilmez bir biyolojik araç olarak değerlendirilmektedir.

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FUSARİUM OXYSPORUM İN STRAWBERRY PRODUCTION SYSTEMS: ETIOLOGY, SYMPTOMATOLOGY, EPIDEMIOLOGICAL COMPLEXITY AND INTEGRATED MANAGEMENT FRAMEWORKS

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ABSTRACT

Strawberry (*Fragaria* × *ananassa* Duch.) is highly susceptible to soilborne pathogens—including *Fusarium oxysporum, Rhizoctonia solani, Macrophomina phaseolina*, and *Phytophthora* spp.—due to its high economic value and intensive production systems. Among these pathogens, *Fusarium oxysporum* is of particular importance because of its long-term persistence in soil and its ability to colonize vascular tissues. The present study examines the etiology of *F. oxysporum* in strawberry production systems, host–pathogen interactions, symptom development, and epidemiological dynamics from an integrated disease management perspective. *F. oxysporum* is characterized by high genetic variability, host specificity, and a strong capacity for systemic colonization. Climate change—manifested through rising temperatures and irregular precipitation patterns—intensifies physiological stress in plants, thereby promoting pathogen growth and enhancing virulence. Notably, the marked increase in disease severity within the 24–28 °C temperature range renders risk projections under global warming scenarios particularly critical. The soil microbiome represents a decisive yet often overlooked component of this pathosystem. In suppressive soils, high microbial diversity and functional redundancy can limit *Fusarium* populations through mechanisms such as niche competition, hyperparasitism, antibiosis, and induced systemic resistance (ISR). In contrast, intensive monoculture and chemically dependent production systems may disrupt microbial balance, creating a rhizosphere environment favorable to the pathogen. Climate change has the potential not only to increase pathogen aggressiveness but also to alter microbial community composition, thereby weakening disease suppressiveness. *Fusarium oxysporum* f. sp. *fragariae*, the causal agent of vascular wilt, establishes systemic infection through mycelial growth within xylem tissues and the transport of microconidia. Disease symptoms typically begin with chlorosis and wilting of lower leaves, progressing to vascular browning, stunting, and eventual plant death. Latent infections and asymptomatic carriers further increase epidemiological complexity. Environmental factors constitute major determinants of disease severity, while monoculture practices and climate change facilitate pathogen dissemination. This study emphasizes strategies such as the development of resistant cultivars, certified nursery systems, and biological control agents, and highlights the importance of molecular diagnostic techniques and early detection systems. In conclusion, the management of *F. oxysporum*-induced wilt requires a multilayered approach. The implementation of integrated and sustainable disease management strategies is of strategic importance for reducing economic losses and minimizing environmental risks.

Keywords: Climate change, *Fragaria* × *ananassa*, Fusarium wilt, Pathogenesis, Root rot

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ÇİLEK ÜRETİM SİSTEMLERİNDE *Fusarium oxysporum*: ETİYOLOJİ, SİMPTOMATOLOJİ, EPİDEMİYOLOJİK KARMAŞIKLIK VE ENTEGRE HASTALIK YÖNETİMİ ÇERÇEVELERİ

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ÖZET

Çilek (*Fragaria* × *ananassa* Duch.) yüksek ekonomik değeri nedeniyle toprak kökenli patojenlere *Fusarium oxysporum*, *Rhizoctonia solani, Macrophomina phaseolina, Phytophthora* spp.) karşı hassas bir bitkidir. Bu patojenlerden biri olan *Fusarium oxysporum*, uzun süreli toprak canlılığı ve iletim demetlerinde kolonizasyon yeteneği sayesinde önemlidir. Yapılan bu çalışma, *F. oxysporum*'un çilek üretim sistemlerindeki etiyolojisini, konukçu-patojen etkileşimlerini, semptom gelişimini ve epidemiyolojik dinamiklerini entegre bir hastalık yönetimi perspektifiyle incelemektedir. *F. oxysporum*, yüksek genetik varyabilitesi ve konukçu özgüllüğü ile sistemik kolonizasyon yetenekleri bulunur. İklim değişikliği, sıcaklık artışları ve düzensiz yağışlarla birlikte, bitkilerdeki fizyolojik stresi artırarak patojenin büyümesine ve virülansına katkıda bulunmaktadır. Özellikle 24–28 °C sıcaklık aralığında hastalık şiddetinin artması, küresel ısınma senaryolarında risk projeksiyonlarını kritik hale getirmektedir. Toprak mikrobiyomu ise bu patosistemin belirleyici ancak çoğu zaman göz ardı edilen bileşenidir. Baskılayıcı (suppressive) topraklarda mikrobiyal çeşitlilik ve fonksiyonel redundans yüksek olup, niş rekabeti, hiperparazitizm, antibiyozis ve uyarılmış sistemik direnç (ISR) mekanizmaları yoluyla *Fusarium* popülasyonlarını sınırlandırabilmektedir. Buna karşılık, yoğun monokültür ve kimyasal girdilere dayalı üretim sistemleri mikrobiyal dengeyi bozarak patojen lehine bir rizosfer ortamı oluşturabilmektedir. İklim değişikliği, yalnızca patojeni değil, mikrobiyal topluluk kompozisyonunu da değiştirerek hastalık baskılayıcılığını zayıflatma potansiyeline sahiptir. *F. oxysporum* f. sp. *fragariae*, vasküler solgunluk etmeni olarak kislem dokusunda miselyal gelişim ve mikrokonidial taşınım yoluyla sistemik enfeksiyon oluşturur. Hastalık belirtileri, alt yapraklarda kloroz ve solgunlukla başlar, ilerleyerek iletim demetlerinde kahverengileşme, bodurlaşma ve bitki ölümüne neden olabilir. Latent enfeksiyonlar ve semptomsuz taşıyıcılık, epidemiyolojik karmaşıklığı artırır. Çevresel faktörler, hastalık şiddetini etkileyen önemli unsurlar arasındadır. Monokültür ve iklim değişikliği, patojenin yayılımını teşvik etmektedir. Çalışma, dayanıklı çeşit geliştirme, fide sertifikasyon sistemleri, biyolojik kontrol ajanları gibi stratejilere odaklanmakta; moleküler tanı teknikleri ve erken teşhis sistemlerinin önemi vurgulanmaktadır. Sonuç olarak, *F. oxysporum* kaynaklı solgunluk hastalığının yönetimi, çok katmanlı bir yaklaşım gerektirirken, entegre ve sürdürülebilir hastalık yönetimi, ekonomik kayıpların azaltılması ve çevresel risklerin en aza indirilmesi açısından stratejik öneme sahiptir.

Anahtar Kelimeler: Fragaria × ananassa, Fusarium solgunluğu, İklim değişikliği, Kök çürüklüğü, Patogenez

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1. Giriş

Çilek (*Fragaria* × *ananassa* Duch.), yüksek ekonomik değeri, geniş adaptasyon kapasitesi, kısa üretim döngüsü ve tüketici talebindeki sürekli artış nedeniyle dünya genelinde stratejik öneme sahip meyve türlerinden biridir. Taze tüketim yanında işlenmiş gıda endüstrisinde de yoğun olarak kullanılan çilek, yüksek antioksidan kapasitesi, vitamin içeriği ve fonksiyonel besin özellikleri nedeniyle küresel pazarda önemli bir ticari ürün konumundadır (FAO, 2024). Dünya genelinde çilek üretimi son yıllarda hızlı bir artış göstermiş; özellikle yoğun yetiştiricilik sistemlerinin yaygınlaşmasıyla birlikte birim alandan elde edilen verim yükselmiştir. Türkiye ise uygun ekolojik koşulları sayesinde dünya çilek üretiminde önemli üretici ülkeler arasında yer almakta olup, özellikle Akdeniz ve Ege bölgelerinde yoğun üretim gerçekleştirilmektedir. Bununla birlikte modern üretim sistemlerinde artan monokültür uygulamaları, yüksek fide sirkülasyonu, yoğun kimyasal kullanımına dayalı yetiştiricilik ve iklimsel düzensizlikler, çilek üretim sistemlerini toprak kökenli patojenlere karşı daha kırılgan hale getirmiştir.

Çilek yetiştiriciliğinde verim ve kalite kayıplarına neden olan en önemli biyotik stres faktörlerinden biri toprak kökenli fungal patojenlerdir. Özellikle *Fusarium oxysporum, Rhizoctonia solani, Macrophomina phaseolina* ve *Phytophthora* spp. gibi patojenler kök ve taç çürüklükleri ile vasküler solgunluk hastalıklarına neden olarak ciddi ekonomik kayıplar oluşturmaktadır (Fang vd., 2012; Maas, 1998). Bu patojenler arasında *Fusarium oxysporum*, yüksek adaptasyon yeteneği, uzun süreli toprak canlılığı ve ksilem dokusunda sistemik kolonizasyon kapasitesi nedeniyle ayrı bir öneme sahiptir. Özellikle *F. oxysporum* f. sp. *fragariae*, çilekte vasküler solgunluk hastalığının temel etmeni olarak tanımlanmakta ve dünya genelinde birçok üretim alanında önemli verim kayıplarına neden olmaktadır (Henry vd., 2017).

Fusarium oxysporum tür kompleksi, yüksek genetik varyabiliteye sahip olması nedeniyle fitopatolojik açıdan oldukça karmaşık bir yapı göstermektedir. Tür içerisindeki forma specialis düzeyindeki farklılaşmalar, patojenin belirli konukçulara özelleşmesine olanak tanımaktadır. Bu durum, hastalık yönetimini zorlaştıran temel unsurlardan biri olarak değerlendirilmektedir. Patojenin kök dokusundan giriş yaptıktan sonra ksilem elementlerinde miselyal gelişim göstermesi ve mikrokonidiler aracılığıyla sistemik yayılım gerçekleştirmesi, iletim demetlerinde tıkanmalara ve sonuç olarak su iletiminde ciddi bozulmalara neden olmaktadır (Beckman, 1987). Hastalık belirtileri genellikle alt yapraklarda kloroz, solgunluk ve gelişme geriliği şeklinde başlamakta; ilerleyen dönemlerde ksilem dokusunda kahverengileşme, taç nekrozu ve bitki ölümü ile sonuçlanabilmektedir. Bunun yanında latent enfeksiyonların varlığı ve semptomsuz fide materyallerinin taşınabilmesi, epidemiyolojik süreçleri daha karmaşık hale getirmektedir.

Son yıllarda iklim değişikliğinin bitki hastalıkları üzerindeki etkileri, tarımsal fitopatoloji çalışmalarının temel araştırma alanlarından biri haline gelmiştir. Artan sıcaklıklar, düzensiz yağış rejimleri ve kuraklık stresinin çilek bitkisinde fizyolojik baskıyı artırdığı; bunun sonucunda ise *F. oxysporum* enfeksiyonlarına duyarlılığın yükseldiği bildirilmektedir (Garrett vd., 2006). Özellikle 24–28 °C sıcaklık aralığında patojen gelişimi ve hastalık şiddetinin belirgin şekilde arttığı ifade

edilmektedir. Bu durum, küresel ısınma senaryoları altında çilek üretim sistemlerinde Fusarium solgunluğunun gelecekte daha büyük epidemiyolojik tehdit oluşturabileceğini göstermektedir. Ayrıca iklim değişikliği yalnızca patojeni değil, aynı zamanda toprak mikrobiyal topluluklarını da etkileyerek hastalık baskılayıcılığında azalmaya neden olabilmektedir.

Toprak mikrobiyomu, bitki sağlığı ve hastalık gelişimi açısından kritik öneme sahip biyolojik bir ekosistem bileşenidir. Özellikle baskılayıcı (suppressive) topraklarda bulunan yüksek mikrobiyal çeşitlilik, patojen popülasyonlarının doğal yollarla sınırlandırılmasına katkı sağlamaktadır. Faydalı mikroorganizmalar; niş rekabeti, antibiyozis, hiperparazitizm ve uyarılmış sistemik direnç (ISR) mekanizmaları yoluyla *Fusarium* popülasyonlarını baskılayabilmektedir (Mendes vd., 2011). Buna karşın yoğun monokültür sistemleri ile aşırı fungisit ve kimyasal gübre kullanımına dayalı modern yetiştiricilik uygulamaları, rizosfer mikrobiyal dengesini bozarak patojen lehine bir ortam oluşturabilmektedir. Bu nedenle günümüzde yalnızca patojene odaklanan klasik mücadele stratejileri yerine, mikrobiyom merkezli sürdürülebilir hastalık yönetimi yaklaşımları ön plana çıkmaktadır.

Çilekte Fusarium solgunluğu ile mücadelede kimyasal yöntemler uzun yıllar temel kontrol stratejisi olarak uygulanmış olsa da fungisit direnci, çevresel kirlilik, kalıntı problemleri ve toprak biyotasına olan olumsuz etkiler nedeniyle bu yöntemlerin sürdürülebilirliği tartışmalı hale gelmiştir (Dean vd., 2012). Bu nedenle dayanıklı çeşit geliştirme, sertifikalı fide kullanımı, biyolojik mücadele ajanları, moleküler tanı sistemleri ve entegre hastalık yönetimi stratejileri giderek daha fazla önem kazanmaktadır. Özellikle *Trichoderma* spp., *Bacillus* spp. ve *Pseudomonas* spp. gibi biyolojik kontrol ajanlarının hem doğrudan antagonistik etki hem de bitkide sistemik direnç mekanizmalarını aktive etme potansiyeli nedeniyle umut verici olduğu bildirilmektedir.

Bu derleme çalışmasında, çilek üretim sistemlerinde önemli bir vasküler solgunluk etmeni olan *Fusarium oxysporum*'un etiyolojisi, konukçu-patojen etkileşimleri, semptom gelişimi ve epidemiyolojik dinamikleri güncel literatür çerçevesinde değerlendirilmiştir. Ayrıca iklim değişikliği, toprak mikrobiyomu ve modern üretim sistemlerinin hastalık gelişimine etkileri tartışılarak, sürdürülebilir ve entegre hastalık yönetimi stratejilerine yönelik güncel yaklaşımlar kapsamlı şekilde ele alınmıştır.

2. *Fusarium oxysporum*'un Taksonomisi, Biyolojisi ve Etiyolojisi

2.1. Taksonomik Konum ve Genetik Çeşitlilik

Fusarium oxysporum, Ascomycota bölümü, Sordariomycetes sınıfı, Hypocreales takımı ve Nectriaceae familyası içerisinde yer alan kozmopolit bir fungal tür kompleksidir. Tür ilk olarak Schlechtendahl tarafından tanımlanmış olup, daha sonra Snyder ve Hansen tarafından yeniden sınıflandırılarak modern taksonomik çerçevesi oluşturulmuştur (Snyder & Hansen, 1940). Günümüzde *F. oxysporum*, morfolojik açıdan birbirine oldukça benzeyen ancak genetik, fizyolojik ve patojenik özellikler bakımından farklılık gösteren izolatlardan oluşan bir "species complex"

olarak değerlendirilmektedir. Bu nedenle "*Fusarium oxysporum species complex* (FOSC)" terimi yaygın olarak kullanılmaktadır (O'Donnell vd., 2009).

FOSC içerisindeki en dikkat çekici biyolojik özelliklerden biri konukçu özgüllüğüdür. Bu özellik doğrultusunda patojen, enfekte ettiği bitki türüne göre "forma specialis" düzeyinde sınıflandırılmaktadır. Günümüzde 120'den fazla forma specialis tanımlanmış olup, bunlardan biri olan *Fusarium oxysporum* f. sp. *fragariae* çilekte vasküler solgunluk hastalığının temel etmeni olarak bilinmektedir (Armstrong & Armstrong, 1981). Forma specialis kavramı, patojenin belirli konukçulara adaptasyonunu açıklamak açısından önemli olmakla birlikte, moleküler çalışmalar aynı forma specialis içerisindeki izolatların dahi yüksek düzeyde genetik varyasyon gösterebildiğini ortaya koymuştur. Özellikle yatay gen transferleri, kromozomal yeniden düzenlenmeler ve patojenisite kromozomlarının hareketliliği, FOSC'nin evrimsel başarısında kritik rol oynamaktadır (Ma vd., 2010).

Son yıllarda gerçekleştirilen genomik çalışmalar, *F. oxysporum* izolatlarının "çekirdek genom" ve "aksesuar genom" olmak üzere iki temel genomik yapıdan oluştuğunu göstermiştir. Çekirdek genom yaşamsal metabolik süreçlerden sorumluyken, aksesuar genom patojenisite, virülans ve konukçu adaptasyonu ile ilişkili genleri içermektedir. Özellikle "Secreted in Xylem" (SIX) olarak tanımlanan efektör genlerin, konukçu özgüllüğü ve vasküler kolonizasyon süreçlerinde önemli rol oynadığı bildirilmektedir (de Sain & Rep, 2015). SIX genleri aynı zamanda moleküler tanı çalışmalarında biyobelirteç olarak kullanılmaktadır.

FOSC içerisindeki genetik çeşitliliğin değerlendirilmesinde vegetatif uyum grupları (Vegetative Compatibility Groups; VCG) önemli bir araçtır. VCG analizleri, izolatlar arasındaki genetik ilişkilerin ve epidemiyolojik bağlantıların belirlenmesine katkı sağlamaktadır. Çilek kökenli *F. oxysporum* izolatlarında farklı VCG gruplarının belirlenmiş olması, patojen popülasyonlarının yüksek adaptasyon kapasitesine sahip olduğunu göstermektedir (Gordon & Martyn, 1997). Bu durum, dayanıklı çeşit geliştirme çalışmalarını ve uzun süreli hastalık yönetimini zorlaştırmaktadır.

2.2. Morfolojik ve Kültürel Özellikler

Fusarium oxysporum, kültürel ve mikromorfolojik özellikleri bakımından karakteristik yapılar oluşturan filamentöz bir fungustur. Patojenin koloni morfolojisi kullanılan besi ortamına, sıcaklığa, ışık koşullarına ve izolatın genetik yapısına bağlı olarak değişiklik gösterebilmektedir. Patates Dekstroz Agar (PDA) ortamında koloniler genellikle beyaz, açık pembe, mor veya menekşe tonlarında gelişim göstermektedir. Bazı izolatlarda yoğun havai miselyum oluşumu gözlenirken, bazı kültürlerde ise kompakt ve düşük yoğunluklu gelişim meydana gelmektedir (Leslie & Summerell, 2006).

F. oxysporum'un en önemli mikroskobik yapılarından biri mikrokonidilerdir. Mikrokonidiler genellikle tek hücreli, oval veya elipsoidal yapıdadır ve kısa fialidlerden yalancı başçıklar halinde

oluşmaktadır. Bu yapılar ksilem dokusunda sistemik taşınım açısından kritik öneme sahiptir. Makrokonidiler ise ince duvarlı, hilal biçiminde ve çoğunlukla üç ila beş septalı yapı göstermektedir. Makrokonidilerin uç hücreleri hafif kıvrık ve sivri yapıdadır. Türün tanısında önemli bir diğer yapı ise klamidosporlardır. Klamidosporlar terminal veya interkalar şekilde oluşabilmekte ve patojenin uzun süre toprakta canlı kalabilmesini sağlamaktadır (Booth, 1971).

Klamidospor oluşumu, *F. oxysporum*'un epidemiyolojik başarısında temel belirleyicilerden biridir. Bu yapılar olumsuz çevresel koşullara karşı oldukça dayanıklıdır ve toprakta yıllarca canlılığını sürdürebilmektedir. Özellikle çilek üretim alanlarında rotasyon uygulanmayan sistemlerde klamidospor yoğunluğunun artması, inokulum baskısının yükselmesine neden olmaktadır. Ayrıca patojenin kök artıklarında saprofitik yaşam sürdürebilmesi, inokulum kaynaklarının sürekliliğini desteklemektedir.

Selektif besi ortamlarında yapılan izolasyon çalışmaları, *F. oxysporum*'un hızlı gelişim kapasitesine sahip olduğunu göstermektedir. Komada'nın seçici besiyeri, Nash-Snyder ortamı ve peptone-PCNB bazlı ortamlar patojenin izolasyonunda yaygın olarak kullanılmaktadır (Komada, 1975). Bununla birlikte yalnızca morfolojik kriterlere dayalı tanı yöntemleri, FOSC içerisindeki yüksek varyasyon nedeniyle yetersiz kalabilmektedir. Bu nedenle günümüzde moleküler identifikasyon yöntemleri klasik tanı sistemleriyle birlikte kullanılmaktadır.

2.3. Yaşam Döngüsü ve Toprakta Hayatta Kalma Mekanizmaları

Fusarium oxysporum, yaşam döngüsünün büyük bölümünü toprak ekosistemi içerisinde sürdüren ve hem saprofitik hem de patojenik yaşam stratejilerini başarıyla kullanabilen toprak kökenli bir fungustur. Türün ekolojik başarısının temelinde, uzun süre canlı kalabilme kapasitesi, geniş çevresel adaptasyon yeteneği ve farklı biyolojik nişlerde yaşamını sürdürebilmesi yer almaktadır. Özellikle çilek üretim sistemlerinde *F. oxysporum f. sp. fragariae*'nin yıllarca toprakta canlılığını koruyabilmesi, hastalık yönetimini zorlaştıran en önemli epidemiyolojik faktörlerden biri olarak kabul edilmektedir (Gordon & Martyn, 1997).

Patojenin yaşam döngüsünün merkezinde klamidospor oluşumu yer almaktadır. Klamidosporlar kalın hücre duvarına sahip dormant yapılar olup, olumsuz çevresel koşullara karşı yüksek dayanıklılık göstermektedir. Bu yapılar terminal veya interkalar şekilde oluşabilmekte ve toprakta uzun yıllar canlı kalabilmektedir (Booth, 1971). Klamidosporların düşük sıcaklık, kuraklık, düşük besin düzeyi ve mikrobiyal rekabet gibi stres koşullarına dayanabilmesi, *F. oxysporum*'un persistens kapasitesini artırmaktadır. Özellikle monokültür çilek üretim alanlarında inokulum yoğunluğunun yıllar içerisinde progresif şekilde artması, büyük ölçüde klamidospor rezervlerinin birikimi ile ilişkilendirilmektedir.

Toprakta dormant halde bulunan klamidosporların çimlenmesi, büyük ölçüde çevresel koşullar ve konukçu köklerinden salınan eksudatlar tarafından düzenlenmektedir. Çilek köklerinden salgılanan aminoasitler, karbonhidratlar, organik asitler ve fenolik bileşikler, patojen için güçlü

kemotaktik sinyaller oluşturmaktadır (Bais vd., 2006). Bu kök eksudatları yalnızca klamidospor çimlenmesini teşvik etmekle kalmamakta, aynı zamanda fungal metabolizmayı aktive ederek germ tüpü oluşumunu başlatmaktadır. Böylece dormant yapıdan aktif enfeksiyon aşamasına geçiş gerçekleşmektedir.

Klamidospor → Çimlenme→ Kök kolonizasyonu → Ksilem yayılımı → Sistemik Yayılım

Çimlenme sonrasında oluşan germ tüpleri rizosfer bölgesine yönelmekte ve kök yüzeyinde kolonizasyon gerçekleştirmektedir. Rizoplana yerleşen fungal hifler, özellikle genç kök uçları ve lateral kök çıkış bölgelerinde yoğunlaşmaktadır. Bu bölgeler hücre duvarlarının nispeten ince olması ve aktif hücre bölünmesinin gerçekleşmesi nedeniyle penetrasyona daha duyarlıdır. Penetrasyon sonrasında fungus önce epidermis ve korteks dokularında sınırlı bir gelişim göstermekte, ardından ksilem elemanlarına ulaşarak vasküler kolonizasyonu başlatmaktadır (Beckman, 1987).

F. oxysporum'un yaşam döngüsünde saprofitik faz oldukça önemlidir. Patojen yalnızca canlı bitki dokularında değil, aynı zamanda bitki artıklarında da yaşamını sürdürebilmektedir. Hasat sonrası toprakta bırakılan enfekteli kök ve taç dokuları, inokulumun devamlılığı açısından kritik rezervuar görevi görmektedir. Fungus bu organik materyaller üzerinde saprofitik gelişim göstererek yeni klamidosporlar oluşturmakta ve böylece toprak inokulum yükünü artırmaktadır (Edel-Hermann & Lecomte, 2019). Özellikle yoğun üretim sistemlerinde bitki artıklarının yeterince uzaklaştırılmaması, hastalık döngüsünün sürekliliğini desteklemektedir.

Patojenin hayatta kalma stratejilerinden biri de asemptomatik konukçu kolonizasyonudur. *F. oxysporum*, bazı yabancı ot türleri ve alternatif konukçular üzerinde belirti oluşturmaksızın kolonizasyon gerçekleştirebilmektedir. Bu durum, inokulumun tarımsal üretim olmayan dönemlerde de korunmasına olanak sağlamaktadır. Özellikle yabancı otların yoğun olduğu üretim alanlarında patojen popülasyonlarının daha stabil kaldığı bildirilmektedir (Gordon, 2017). Dolayısıyla yabancı ot yönetimi, yalnızca rekabet kontrolü açısından değil, aynı zamanda epidemi yönetimi bakımından da önem taşımaktadır.

Toprak fiziksel ve kimyasal özellikleri, *F. oxysporum*'un yaşam döngüsünü doğrudan etkileyen temel faktörler arasında yer almaktadır. Hafif tekstürlü ve drenajı zayıf topraklarda hastalık gelişiminin daha yüksek olduğu bildirilmektedir. Benzer şekilde düşük organik madde düzeyi ve yoğun azotlu gübreleme uygulamaları, patojenin rizosfer kolonizasyon kapasitesini artırabilmektedir. Toprak pH'sının ise hem patojen gelişimi hem de mikrobiyal rekabet üzerinde belirleyici etkileri bulunmaktadır. Nötr ve hafif asidik koşulların patojen gelişimini desteklediği ifade edilmektedir (Jones vd., 2014).

Sıcaklık, yaşam döngüsünün şekillenmesinde kritik rol oynayan çevresel parametrelerden biridir. Özellikle yüksek sıcaklık koşulları, klamidospor çimlenmesini ve miselyal gelişimi hızlandırmaktadır. Çalışmalar, *F. oxysporum* gelişimi için optimum sıcaklık aralığının yaklaşık 24–

28 °C olduğunu göstermektedir. Bu sıcaklık aralığında hem rizosfer kolonizasyonu hem de vasküler invazyon önemli ölçüde artmaktadır. Küresel iklim değişikliğiyle birlikte sıcaklık artışlarının yaygınlaşması, gelecekte Fusarium solgunluğu epidemilerinin daha şiddetli hale gelebileceğine işaret etmektedir (Garrett vd., 2006).

Toprak mikrobiyomu, *F. oxysporum*'un yaşam döngüsü üzerinde baskılayıcı veya teşvik edici etkilere sahip olabilmektedir. Baskılayıcı topraklarda bulunan faydalı bakteriler ve antagonist funguslar, klamidospor çimlenmesini inhibe edebilmekte veya fungal gelişimi baskılayabilmektedir. Özellikle *Trichoderma*, *Bacillus* ve fluoresan *Pseudomonas* türlerinin antifungal metabolit üretimi, siderofor salgılanması ve niş rekabeti yoluyla inokulum yoğunluğunu azalttığı bildirilmektedir (Mendes vd., 2011). Buna karşın yoğun fungisit kullanımına dayalı üretim sistemleri, mikrobiyal çeşitliliği azaltarak patojen lehine bir rizosfer ortamı oluşturabilmektedir.

Son yıllarda yapılan çalışmalar, *F. oxysporum*'un biyofilm benzeri yapılar oluşturabildiğini ve bu durumun çevresel stres toleransını artırdığını göstermektedir. Özellikle kök yüzeyinde gelişen yoğun miselyal ağ yapılarının, patojenin rizosferde daha stabil kolonizasyon gerçekleştirmesine katkı sağladığı düşünülmektedir. Ayrıca aksesuar kromozomlarda bulunan patojenisite genlerinin yatay transfer kapasitesi, yeni çevresel koşullara hızlı adaptasyon sağlanmasında önemli rol oynamaktadır (Ma vd., 2010).

Yaşam döngüsünün son aşamasında enfekte bitki dokularının parçalanmasıyla birlikte fungus yeniden toprağa dönmekte ve yeni klamidospor oluşumlarıyla döngü devam etmektedir. Bu nedenle *F. oxysporum* epidemiyolojisi yalnızca aktif enfeksiyon süreçlerinden değil, aynı zamanda uzun süreli toprak persistensi ve mikrobiyal ekolojik etkileşimlerden oluşan kompleks bir sistem olarak değerlendirilmelidir. Hastalık yönetiminde yalnızca mevcut enfeksiyonların kontrol edilmesi yeterli olmayıp, aynı zamanda toprak inokulum rezervlerinin azaltılmasına yönelik stratejilerin geliştirilmesi gerekmektedir.

2.4. Enfeksiyon Biyolojisi ve Hastalık Oluşumu

Fusarium oxysporum'un enfeksiyon biyolojisi, konukçu bitki, patojen ve çevresel faktörler arasında gerçekleşen çok aşamalı ve dinamik etkileşimlerden oluşmaktadır. Özellikle vasküler sistemde kolonizasyon yeteneğine sahip olması, bu patojeni diğer birçok toprak kökenli fungustan ayıran en önemli özelliklerden biridir. Enfeksiyon süreci yalnızca fiziksel penetrasyon ile sınırlı olmayıp; moleküler sinyalizasyon, efektör protein salgılanması, konukçu bağışıklık sisteminin baskılanması ve metabolik yeniden programlama gibi karmaşık biyolojik mekanizmaları içermektedir (Di Pietro vd., 2003).

Enfeksiyonun ilk aşaması, patojenin rizosfer bölgesinde konukçu köklerinden salınan eksudatları algılamasıyla başlamaktadır. Çilek köklerinden salınan aminoasitler, organik asitler,

şekerler ve fenolik bileşikler, klamidospor çimlenmesini ve hif gelişimini teşvik etmektedir. Özellikle karbon kaynakları bakımından zengin kök eksudatları, dormant halde bulunan klamidosporların metabolik olarak aktive olmasına neden olmaktadır (Bais vd., 2006). Çimlenen klamidosporlardan gelişen germ tüpleri, kemotropik yönelim mekanizmaları sayesinde kök yüzeyine doğru ilerlemekte ve rizoplana kolonizasyonu gerçekleştirmektedir.

Patojenin bitkiye girişinde genç kök uçları, lateral kök çıkış bölgeleri ve mekanik olarak zarar görmüş dokular önemli enfeksiyon noktalarıdır. Bununla birlikte bazı araştırmalar, *F. oxysporum*'un doğrudan epidermal penetrasyon gerçekleştirebildiğini de göstermektedir. Penetrasyon sürecinde fungus, pektinaz, selülaz, ksilanaz ve proteaz gibi hücre duvarı parçalayıcı enzimler salgılayarak bitki hücre duvarını zayıflatmaktadır (Di Pietro vd., 2003). Özellikle poligalakturonaz aktivitesinin, kök korteks dokularının parçalanmasında kritik rol oynadığı bildirilmektedir. Hücre duvarı degradasyonu yalnızca fiziksel penetrasyonu kolaylaştırmamakta, aynı zamanda enfeksiyon bölgesinde besin açığa çıkışını artırarak fungal gelişimi desteklemektedir.

Korteks dokusunu geçen fungal hifler daha sonra endodermise ulaşmakta ve ksilem elemanlarına giriş yapmaktadır. Ksilem kolonizasyonu, *F. oxysporum* patogenezinin merkezi aşamasını oluşturmaktadır. Fungus burada hem miselyal gelişim göstermekte hem de yoğun şekilde mikrokonidi üretmektedir. Ksilem içerisindeki transpirasyon akımı, mikrokonidilerin yukarı taşınmasını sağlayarak enfeksiyonun sistemik hale gelmesine neden olmaktadır (Beckman, 1987). Böylece patojen kısa sürede taç dokusu ve üst vegetatif organlara ulaşabilmektedir.

Vasküler kolonizasyon sürecinde patojen tarafından salgılanan efektör proteinler, konukçu savunma sisteminin baskılanmasında önemli rol oynamaktadır. Özellikle "Secreted in Xylem" (SIX) proteinleri, *F. oxysporum* patogenezinde en iyi tanımlanmış virülans faktörleri arasında yer almaktadır. SIX proteinleri ksilem özsuyuna salgılanmakta ve bitki bağışıklık yanıtlarını manipüle ederek fungal gelişim için uygun bir ortam oluşturmaktadır (de Sain & Rep, 2015). Bazı SIX genlerinin belirli formae speciales ile ilişkili olması, bu efektörlerin konukçu özgüllüğünde de rol oynadığını göstermektedir. Ayrıca aksesuar kromozomlarda taşınan patojenisite genlerinin yatay transferi, yeni virülent popülasyonların oluşmasına katkı sağlayabilmektedir (Ma vd., 2010).

Bitki, enfeksiyona karşı çeşitli savunma mekanizmaları geliştirmektedir. Bunlar arasında fenolik bileşik birikimi, lignifikasyon, reaktif oksijen türlerinin (ROS) üretimi, kalloz depozisyonu ve tylosis oluşumu yer almaktadır. Tylosisler, ksilem elemanlarını tıkayan parankima hücre uzantıları olup patojen yayılımını sınırlandırmaya yönelik bir savunma yanıtıdır. Ancak yoğun fungal kolonizasyon durumunda bu yapıların aşırı oluşumu su iletimini ciddi şekilde engelleyebilmektedir (Yadeta & Thomma, 2013). Sonuç olarak bitkide su stresi gelişmekte ve yapraklarda solgunluk belirtileri ortaya çıkmaktadır.

Hastalığın ilerleyen dönemlerinde ksilem elemanlarında fungal biyokütle, tylosis ve jel benzeri maddelerin birikmesi vasküler tıkanıklığı artırmaktadır. Bu durum transpirasyon dengesinin

bozulmasına, stomatal kapanmaya ve fotosentetik kapasitenin düşmesine neden olmaktadır. Aynı zamanda enfekte bitkilerde klorofil içeriğinin azaldığı, lipid peroksidasyonunun arttığı ve antioksidan enzim aktivitelerinde önemli değişimler meydana geldiği bildirilmektedir. Özellikle peroksidaz (POX), polifenol oksidaz (PPO) ve süperoksit dismutaz (SOD) aktivitelerindeki değişimler, bitkinin oksidatif stres yanıtı ile ilişkilendirilmektedir (Michielse & Rep, 2009).

Çevresel koşullar, enfeksiyon biyolojisinin şekillenmesinde belirleyici rol oynamaktadır. Özellikle yüksek sıcaklık ve düşük toprak nemi, çilek bitkisinde fizyolojik stres oluşturarak hastalığın şiddetini artırmaktadır. Patojen gelişimi için optimum sıcaklık aralığının yaklaşık 24–28 °C olması, iklim değişikliği senaryolarında Fusarium solgunluğunun daha büyük epidemiyolojik tehdit oluşturabileceğini göstermektedir. Ayrıca yoğun azotlu gübreleme uygulamalarının ve düşük organik madde içeriğinin, hastalık gelişimini teşvik ettiği bildirilmektedir (Jones vd., 2014).

F. oxysporum enfeksiyonlarının en problematik özelliklerinden biri latent enfeksiyon kapasitesidir. Patojen, belirti oluşturmaksızın fide dokularında uzun süre canlı kalabilmekte ve uygun çevresel koşullar oluştuğunda aktif enfeksiyona geçebilmektedir. Bu durum özellikle sertifikasız fide kullanımında önemli epidemiyolojik risk oluşturmaktadır. Semptomsuz enfekteli fidelerin üretim alanlarına taşınması, hastalığın yeni bölgelere yayılmasında temel bulaşma yollarından biri olarak kabul edilmektedir (Henry vd., 2017).

Son yıllarda yapılan çalışmalar, *F. oxysporum* enfeksiyon biyolojisinin yalnızca patojen-konukçu etkileşiminden ibaret olmadığını; aynı zamanda rizosfer mikrobiyomunun da bu süreçte aktif rol oynadığını ortaya koymuştur. Baskılayıcı topraklarda bulunan faydalı bakteriler ve fungal antagonistlerin, patojenin kök kolonizasyonunu baskılayabildiği bildirilmektedir. Özellikle *Trichoderma*, *Bacillus* ve *Pseudomonas* türleri; antibiyotik üretimi, siderofor salgılanması, niş rekabeti ve ISR mekanizmaları yoluyla enfeksiyon sürecini sınırlandırabilmektedir (Mendes vd., 2011). Bu nedenle günümüzde enfeksiyon biyolojisi çalışmaları yalnızca patojen odaklı değil, aynı zamanda mikrobiyom merkezli bir perspektifle ele alınmaktadır.

3. Konukçu–Patojen Etkileşimleri ve Hastalık Gelişimi

3.1. Çilekte Savunma Mekanizmaları

Bitkiler, çevresel stres faktörleri ve patojen saldırıları karşısında karmaşık savunma mekanizmaları geliştirmiş organizmalardır. Çilek (*Fragaria × ananassa* Duch.) bitkisi de toprak kökenli vasküler patojenlere karşı çok katmanlı savunma sistemlerine sahiptir. Ancak *Fusarium oxysporum f. sp. fragariae* gibi vasküler kolonizasyon yeteneği yüksek patojenler, bu savunma mekanizmalarını baskılayabilme veya aşabilme kapasitesine sahip olduklarından ciddi hastalık gelişimlerine neden olabilmektedir. Konukçu–patojen etkileşimleri; fiziksel bariyerler, biyokimyasal yanıtlar, moleküler sinyalizasyon süreçleri ve hormonal düzenlemelerden oluşan kompleks bir biyolojik ağ şeklinde gerçekleşmektedir (Yadeta & Thomma, 2013).

Çileğin ilk savunma hattını epidermis, kutikula ve hücre duvarı gibi fiziksel bariyerler oluşturmaktadır. Özellikle lignin, selüloz ve hemiselüloz bakımından zengin hücre duvarı yapıları, fungal penetrasyonu sınırlandırmada önemli rol oynamaktadır. Bununla birlikte *F. oxysporum* tarafından salgılanan hücre duvarı parçalayıcı enzimler, bu bariyerlerin zayıflatılmasına neden olabilmektedir. Pektinaz, selülaz ve ksilanaz gibi enzimler sayesinde patojen, kök epidermisini geçerek korteks dokusuna ulaşabilmektedir (Di Pietro vd., 2003).

Bitki, fungal penetrasyonu algıladıktan sonra "PAMP-triggered immunity" (PTI) olarak tanımlanan temel bağışıklık yanıtını aktive etmektedir. Bu süreçte fungal hücre duvarı bileşenleri olan kitin ve β-glukan gibi moleküller, bitki reseptörleri tarafından tanınmaktadır. Tanıma sonrasında reaktif oksijen türleri (ROS) üretimi, kalsiyum sinyalizasyonu, MAP kinaz aktivasyonu ve savunma genlerinin ekspresyonu tetiklenmektedir (Boller & Felix, 2009). Özellikle hidrojen peroksit birikimi, enfeksiyon bölgesinde antimikrobiyal etki oluşturmasının yanında hücre duvarı güçlenmesine de katkı sağlamaktadır.

Bitkinin savunma yanıtında fenolik bileşiklerin üretimi önemli bir yer tutmaktadır. Fenoller, fitoaleksinler ve lignin prekürsörleri, fungal gelişimi baskılayıcı özellik göstermektedir. Enfeksiyon sürecinde fenilalanin amonyak liyaz (PAL) enziminin aktivitesindeki artış, fenilpropanoid metabolizmasının aktive olduğunu göstermektedir. Bu süreç lignifikasyonu artırarak ksilem dokularının güçlenmesine katkı sağlamaktadır (Michielse & Rep, 2009). Bununla birlikte yoğun fungal kolonizasyon durumunda bu savunma yanıtları çoğu zaman enfeksiyonu tamamen durdurmak için yeterli olmamaktadır.

Çilek bitkisinde savunma yanıtlarının düzenlenmesinde fitohormonlar kritik rol oynamaktadır. Jasmonik asit (JA), etilen (ET) ve salisilik asit (SA) sinyal yolları, patojen savunmasının temel düzenleyicileri arasında yer almaktadır. Nekrotrofik ve hemibiyotrofik patojenlere karşı özellikle JA ve ET aracılı savunma mekanizmalarının daha aktif olduğu bildirilmektedir. *F. oxysporum* enfeksiyonları sırasında jasmonat sinyalizasyonunun aktive olduğu ve savunma genlerinin ekspresyonunu artırdığı belirlenmiştir (Glazebrook, 2005). Ancak patojen tarafından salgılanan bazı efektör proteinler, hormonal sinyal yollarını manipüle ederek bitki savunmasını baskılayabilmektedir.

3.2. Patojenisite ve Virülans Faktörleri

Fusarium oxysporum'un yüksek patojenik kapasitesi, sahip olduğu çok sayıda virülans faktörü ile ilişkilidir. Bu faktörler; hücre duvarı parçalayıcı enzimler, toksinler, efektör proteinler, sideroforlar ve stres tolerans mekanizmalarından oluşmaktadır. Özellikle vasküler sistemde yaşayabilme kapasitesi, patojenin konukçu bitkide sistemik enfeksiyon oluşturmasına olanak sağlamaktadır.

En önemli virülans mekanizmalarından biri hücre duvarı degradasyonudur. Patojen tarafından salgılanan poligalakturonazlar, pektat liyazlar, selülazlar ve ksilanazlar bitki hücre duvarını

parçalayarak fungal penetrasyonu kolaylaştırmaktadır (Di Pietro vd., 2003). Bunun yanında fungal proteazlar, bitkinin savunma proteinlerini hedef alarak bağışıklık sisteminin zayıflamasına neden olabilmektedir.

F. oxysporum patogenezinde düşük molekül ağırlıklı toksik metabolitlerin de önemli rol oynadığı bildirilmektedir. Fusarik asit, en yaygın tanımlanan toksinlerden biridir ve hücre membranı bütünlüğünü bozarak iyon dengesizliği oluşturabilmektedir. Ayrıca toksinlerin ksilem dokusunda hücresel nekrozu artırarak vasküler işlev kaybına katkı sağladığı düşünülmektedir (Bacon vd., 1996).

Patojenisite sürecinde en dikkat çekici moleküler bileşenlerden biri "Secreted in Xylem" (SIX) proteinleridir. Bu efektör proteinler ksilem özsuyuna salgılanmakta ve konukçu savunma mekanizmalarını baskılamaktadır. SIX genlerinin bazıları doğrudan virülans ile ilişkilendirilmiş olup, belirli forma specialis gruplarında karakteristik olarak bulunmaktadır (de Sain & Rep, 2015). Bu efektörlerin aynı zamanda konukçu özgüllüğünde de rol oynadığı düşünülmektedir.

Virülansın belirlenmesinde aksesuar kromozomlar kritik öneme sahiptir. Yapılan genomik çalışmalar, patojenisite genlerinin büyük kısmının hareketli kromozomal bölgelerde bulunduğunu göstermiştir. Bu bölgelerin yatay transfer yoluyla farklı izolatlar arasında taşınabilmesi, yeni virülent popülasyonların oluşmasına neden olabilmektedir (Ma vd., 2010). Bu durum, *F. oxysporum*'un evrimsel esnekliğini ve adaptasyon kapasitesini açıklayan önemli mekanizmalardan biridir.

3.3. Sistemik Kolonizasyon Mekanizmaları

F. oxysporum'un en önemli biyolojik özelliklerinden biri ksilem dokusunda sistemik kolonizasyon gerçekleştirebilmesidir. Bu süreç, enfeksiyonun lokal kök enfeksiyonundan vasküler solgunluk hastalığına dönüşmesinde temel rol oynamaktadır. Korteks dokusunu geçen fungal hifler ksilem elemanlarına ulaştığında, patojen vasküler sistem içerisinde hızla yayılmaya başlamaktadır.

Ksilem içerisindeki düşük besin koşullarına rağmen *F. oxysporum*, yüksek adaptasyon yeteneği sayesinde burada aktif gelişim gösterebilmektedir. Mikrokonidilerin ksilem özsuyunda taşınması, enfeksiyonun yukarı doğru sistemik şekilde ilerlemesine neden olmaktadır (Beckman, 1987). Özellikle transpirasyon akımının güçlü olduğu dönemlerde patojenin yayılımı hızlanmaktadır.

Kök Enfeksiyonu → Ksilem Kolonizasyonu → Mikrokonidial Taşınım → Vasküler Tıkanıklık → Solgunluk

Bitki, ksilem invazyonuna karşı tylosis oluşumu ve jel benzeri savunma maddeleri üretimiyle yanıt vermektedir. Ancak bu savunma mekanizmaları çoğu zaman su iletimini daha da bozarak hastalık belirtilerini şiddetlendirmektedir. Ksilem elemanlarında fungal biyokütle, tylosis ve polisakkarit birikimi sonucunda vasküler tıkanıklık gelişmektedir (Yadeta & Thomma, 2013).

Bunun sonucunda yapraklarda geçici solgunluk, daha sonra ise kalıcı solgunluk belirtileri ortaya çıkmaktadır.

Sistemik kolonizasyon sürecinde bitkide ciddi fizyolojik bozukluklar meydana gelmektedir. Fotosentetik kapasite azalmakta, stomatal iletkenlik düşmekte ve oksidatif stres düzeyi artmaktadır. Ayrıca su potansiyelindeki düşüş nedeniyle büyüme geriliği ve biyokütle kaybı oluşmaktadır. Enfeksiyonun ileri aşamalarında taç nekrozu ve bitki ölümü meydana gelmektedir.

3.4. Latent Enfeksiyonlar ve Semptomsuz Taşıyıcılık

Çilekte Fusarium solgunluğunun epidemiyolojik açıdan en problematik özelliklerinden biri latent enfeksiyon kapasitesidir. Patojen, bitki dokularında belirgin semptom oluşturmadan uzun süre canlı kalabilmekte ve uygun çevresel koşullar oluştuğunda aktif hastalık gelişimine neden olabilmektedir. Bu durum özellikle fide üretim sistemlerinde büyük fitosaniter risk oluşturmaktadır.

Semptomsuz enfekteli fideler, uluslararası fide ticaretinde patojenin yeni bölgelere taşınmasının temel yollarından biri olarak kabul edilmektedir. Görsel kontrollerle sağlıklı olarak değerlendirilen fide materyallerinin moleküler analizlerde enfekteli bulunabilmesi, latent enfeksiyonların önemini ortaya koymaktadır (Henry vd., 2017). Özellikle sıcaklık stresinin artmasıyla birlikte latent enfeksiyonların aktif hale geçtiği bildirilmektedir.

Latent enfeksiyonların epidemiyolojik sonuçları oldukça ciddidir. Hastalık üretim sezonunun erken dönemlerinde fark edilmeyebilir ve inokulum yoğunluğu sessiz şekilde artabilir. Bu durum ani epidemilerin ortaya çıkmasına neden olabilmektedir. Ayrıca latent enfeksiyonlar, sertifikasyon sistemlerinin etkinliğini azaltan temel faktörlerden biridir.

Bu nedenle modern hastalık yönetiminde yalnızca semptomatik bitkilerin uzaklaştırılması yeterli görülmemektedir. Moleküler tanı teknikleri, qPCR tabanlı erken teşhis sistemleri ve sertifikalı fide üretim programları, latent enfeksiyonların kontrolünde stratejik öneme sahiptir. Özellikle yüksek hassasiyetli moleküler tanı sistemleri, epidemiyolojik risklerin azaltılmasında önemli araçlar olarak değerlendirilmektedir.

4. Tanı ve Erken Teşhis Yaklaşımları

4.1. Klasik Tanı Yöntemleri

Çilekte *Fusarium oxysporum f. sp. fragariae* kaynaklı vasküler solgunluk hastalığının etkin şekilde yönetilebilmesi için hızlı, güvenilir ve duyarlı tanı sistemlerinin kullanılması kritik öneme sahiptir. Hastalığın başlangıç dönemlerinde ortaya çıkan belirtilerin çoğu zaman diğer toprak kökenli patojenlerle karışabilmesi, doğru tanının önemini daha da artırmaktadır. Özellikle *Rhizoctonia solani*, *Macrophomina phaseolina* ve *Phytophthora* spp. gibi patojenlerin neden

olduğu kök ve taç çürüklükleri ile Fusarium solgunluğu arasında semptomatik benzerlikler bulunabilmektedir. Bu nedenle tanı süreçlerinde yalnızca semptom değerlendirmesine dayalı yaklaşımlar çoğu zaman yeterli olmamaktadır (Maas, 1998).

Klasik tanı yöntemleri genellikle semptomatik bitki dokularından fungal izolasyon ve morfolojik identifikasyona dayanmaktadır. Hastalıklı bitkilerde en karakteristik belirti, kök boğazı ve taç dokusunda vasküler kahverengileşme oluşumudur. Enfekteli iletim demetlerinden alınan doku parçaları yüzey sterilizasyonu sonrasında Patates Dekstroz Agar (PDA) veya seçici besi ortamlarına aktarılmaktadır. Kültür gelişimi sonrasında koloni morfolojisi, pigment oluşumu, miselyal yapı ve spor morfolojisi değerlendirilerek ön tanı yapılabilmektedir (Leslie & Summerell, 2006). *F. oxysporum* kültürleri genellikle beyaz, açık pembe veya morumsu pigmentasyon göstermektedir. Mikroskobik incelemelerde kısa monofialidlerden oluşan tek hücreli mikrokonidiler, hilal biçimli çok septalı makrokonidiler ve kalın duvarlı klamidosporlar türün karakteristik yapıları arasında yer almaktadır (Booth, 1971). Bununla birlikte *Fusarium* cinsi içerisinde yüksek morfolojik benzerlik bulunması, yalnızca klasik mikoloji temelli identifikasyonların güvenilirliğini sınırlandırmaktadır. Özellikle *Fusarium oxysporum species complex* (FOSC) içerisindeki izolatlarda morfolojik varyasyonların oldukça geniş olması, yanlış tanılama riskini artırmaktadır.

Selektif izolasyon amacıyla Komada besiyeri ve Nash-Snyder ortamı gibi yarı seçici besi ortamları yaygın olarak kullanılmaktadır. Bu ortamlar bakteriyel kontaminasyonu baskılayarak *Fusarium* türlerinin gelişimini teşvik etmektedir (Komada, 1975). Ancak klasik izolasyon yöntemleri zaman alıcıdır ve latent enfeksiyonların belirlenmesinde düşük hassasiyet gösterebilmektedir. Ayrıca çevresel örneklerde düşük inokulum yoğunluğu bulunan durumlarda yanlış negatif sonuçlar ortaya çıkabilmektedir.

4.2. Moleküler Tanı Teknikleri

Son yıllarda moleküler biyolojide yaşanan gelişmeler, *F. oxysporum*'un hızlı ve hassas şekilde tanılanabilmesine olanak sağlamıştır. Moleküler tanı teknikleri özellikle latent enfeksiyonların belirlenmesi, forma specialis düzeyinde ayrım yapılması ve epidemiyolojik çalışmalar açısından büyük önem taşımaktadır. Bu yöntemler klasik izolasyon tekniklerine göre daha kısa sürede sonuç vermekte ve daha yüksek özgüllük sağlamaktadır. Polimeraz Zincir Reaksiyonu (PCR), *F. oxysporum* tanısında en yaygın kullanılan moleküler yöntemlerden biridir. PCR tabanlı tanı sistemlerinde ITS (Internal Transcribed Spacer), TEF-1α (Translation Elongation Factor 1-alpha) ve β-tubulin gibi genomik bölgeler hedef alınmaktadır (O'Donnell vd., 2009). Özellikle TEF-1α gen bölgesi, tür ve forma specialis düzeyinde yüksek ayırım gücü sağlamaktadır.

PCR → DNA Amplifikasyonu → Tür/forma specialis Tanısı

Çilek kökenli *F. oxysporum f. sp. fragariae* izolatlarının tanısında SIX (Secreted in Xylem) efektör genlerine dayalı primer sistemleri geliştirilmiştir. Özellikle SIX1, SIX6 ve SIX8 genlerinin

bazı virülent izolatlarla ilişkili olduğu bildirilmektedir (de Sain & Rep, 2015). Bu gen bölgeleri, forma specialis düzeyinde özgül tanı yapılabilmesine katkı sağlamaktadır. Gerçek zamanlı kantitatif PCR (qPCR) sistemleri, düşük yoğunluklu inokulumların belirlenmesinde yüksek hassasiyet sağlamaktadır. qPCR yöntemleri sayesinde toprak, sulama suyu ve fide materyallerindeki patojen yoğunluğu kantitatif olarak ölçülebilmektedir. Bu durum özellikle latent enfeksiyonların erken teşhisi açısından kritik öneme sahiptir. Ayrıca qPCR sistemlerinin yüksek duyarlılığı, epidemiyolojik modelleme çalışmalarında daha güvenilir veri elde edilmesine olanak sağlamaktadır (Bilodeau vd., 2012).

Loop-mediated isothermal amplification (LAMP) yöntemi, son yıllarda sahada uygulanabilir hızlı tanı sistemleri arasında dikkat çekmektedir. LAMP yöntemi izotermal koşullarda çalıştığı için termal sikler gerektirmemekte ve kısa sürede sonuç verebilmektedir. Özellikle saha koşullarında taşınabilir cihazlarla uygulanabilmesi, bu yöntemin erken teşhis açısından potansiyelini artırmaktadır. LAMP tabanlı sistemlerin düşük maliyetli olması da önemli avantajlarından biridir. Bununla birlikte moleküler tanı yöntemlerinin bazı sınırlılıkları bulunmaktadır. DNA bazlı sistemler canlı ve ölü inokulumu ayırt edemeyebilmektedir. Ayrıca çevresel örneklerde bulunan inhibitör bileşikler PCR reaksiyonlarını olumsuz etkileyebilmektedir. Bu nedenle moleküler yöntemlerin klasik izolasyon teknikleri ve patojenisite testleri ile birlikte değerlendirilmesi önerilmektedir.

4.3. Genomik ve Metagenomik Yaklaşımlar

Yeni nesil dizileme (NGS) teknolojilerindeki gelişmeler, *F. oxysporum* popülasyon biyolojisinin daha ayrıntılı şekilde anlaşılmasına olanak sağlamıştır. Özellikle tüm genom dizileme çalışmaları, patojenin evrimsel yapısı, virülans mekanizmaları ve konukçu adaptasyon süreçleri hakkında önemli bilgiler sunmaktadır. Yapılan genomik analizler, *F. oxysporum*'un çekirdek genom yanında aksesuar kromozomlar taşıdığını ve patojenisite genlerinin büyük ölçüde bu bölgelerde lokalize olduğunu göstermiştir (Ma vd., 2010). Aksesuar kromozomlarda bulunan patojenisite genlerinin yatay transfer yoluyla farklı izolatlara aktarılabilmesi, yeni virülent popülasyonların oluşmasına katkı sağlamaktadır. Bu durum, hastalık epidemiyolojisinin dinamik yapısını açıklayan önemli mekanizmalardan biridir. Ayrıca genomik çalışmalar, farklı formae speciales arasındaki evrimsel ilişkilerin ortaya konulmasına yardımcı olmaktadır.

Metagenomik yaklaşımlar ise yalnızca patojenin değil, aynı zamanda rizosfer mikrobiyomunun da değerlendirilmesine olanak sağlamaktadır. Toprak mikrobiyal topluluklarının yüksek çözünürlüklü analizleri sayesinde baskılayıcı toprakların biyolojik yapısı daha iyi anlaşılabilmektedir. Özellikle hastalık baskılayıcı topraklarda bulunan antagonist bakterilerin ve faydalı fungal toplulukların belirlenmesi, biyolojik mücadele stratejileri açısından önemli fırsatlar sunmaktadır (Mendes vd., 2011). Metabarkodlama teknikleri, çevresel DNA örneklerinden çok sayıda mikroorganizmanın aynı anda tanılanmasını mümkün hale getirmiştir. ITS ve 16S rRNA

tabanlı analizler sayesinde fungal ve bakteriyel topluluk kompozisyonları yüksek hassasiyetle belirlenebilmektedir. Böylece yalnızca patojen yoğunluğu değil, aynı zamanda mikrobiyal ekosistemin genel yapısı da değerlendirilebilmektedir.

4.4. Erken Teşhis Sistemleri ve Dijital Tarım Yaklaşımları

Modern bitki patolojisi çalışmalarında erken teşhis sistemleri, epidemilerin önlenmesi açısından stratejik önem taşımaktadır. Özellikle latent enfeksiyon kapasitesi yüksek olan *F. oxysporum* gibi patojenlerde erken tanı, hastalık yönetiminin temel bileşenlerinden biri olarak değerlendirilmektedir. Günümüzde sensör teknolojileri, uzaktan algılama sistemleri ve yapay zekâ tabanlı analizler bu amaçla giderek daha yaygın kullanılmaktadır. Hiperspektral görüntüleme sistemleri, bitkilerde henüz görsel semptomlar ortaya çıkmadan fizyolojik değişimlerin belirlenmesine olanak sağlamaktadır. Özellikle klorofil fluoresansı, yaprak sıcaklığı ve spektral yansıma parametreleri kullanılarak stres altındaki bitkiler erken dönemde tespit edilebilmektedir (Mahlein, 2016). Böylece Fusarium enfeksiyonları semptom oluşumundan önce belirlenebilmektedir.

Yapay zekâ destekli görüntü işleme sistemleri de hastalık tanısında önemli gelişmeler sağlamıştır. Derin öğrenme algoritmaları kullanılarak yaprak belirtileri, solgunluk şiddeti ve taç nekrozu otomatik olarak analiz edilebilmektedir. Bu sistemler özellikle büyük ölçekli üretim alanlarında hızlı tarama yapılmasına olanak sağlamaktadır. Dijital tarım uygulamaları kapsamında çevresel sensörler kullanılarak sıcaklık, nem, toprak su potansiyeli ve iletkenlik gibi parametreler sürekli izlenebilmektedir. Bu veriler epidemiyolojik modelleme sistemlerine entegre edilerek hastalık risk tahminleri oluşturulmaktadır. Özellikle sıcaklık artışı ile Fusarium epidemileri arasındaki güçlü ilişki göz önüne alındığında, erken uyarı sistemlerinin gelecekte daha büyük önem kazanacağı düşünülmektedir.

F. oxysporum'un etkin yönetimi için klasik mikolojik yöntemlerden moleküler biyolojiye, genomikten yapay zekâ destekli dijital sistemlere kadar çok katmanlı tanı yaklaşımlarının entegre şekilde kullanılması gerekmektedir. Özellikle iklim değişikliği ve yoğun üretim sistemlerinin oluşturduğu yeni epidemiyolojik riskler dikkate alındığında, hızlı ve hassas erken teşhis sistemleri sürdürülebilir çilek üretimi açısından stratejik önem taşımaktadır.

5. Entegre Hastalık Yönetimi Stratejileri

5.1. Entegre Hastalık Yönetiminin Temel Prensipleri

Çilekte *Fusarium oxysporum f. sp. fragariae* kaynaklı vasküler solgunluk hastalığının yönetimi, patojenin uzun süreli toprak kalıcılığı, latent enfeksiyon kapasitesi, geniş çevresel adaptasyonu ve ksilem kolonizasyon yeteneği nedeniyle oldukça güçtür. Özellikle klamidosporların toprakta uzun yıllar canlı kalabilmesi ve enfekteli fide materyalleriyle kolayca taşınabilmesi, yalnızca tek yönlü mücadele yöntemlerinin yetersiz kalmasına neden olmaktadır

(Gordon, 2017). Bu nedenle modern çilek üretim sistemlerinde hastalık yönetimi, kültürel önlemler, biyolojik mücadele, dayanıklı çeşit kullanımı, moleküler tanı sistemleri ve çevresel sürdürülebilirlik ilkelerini kapsayan entegre hastalık yönetimi yaklaşımı çerçevesinde ele alınmaktadır.

Entegre hastalık yönetimi, hastalık baskısını ekonomik zarar eşiğinin altında tutmayı amaçlayan çok katmanlı bir stratejidir. Bu yaklaşım yalnızca patojeni baskılamayı değil; aynı zamanda toprak sağlığının korunmasını, mikrobiyal dengenin sürdürülebilirliğini ve çevresel risklerin azaltılmasını hedeflemektedir (Agrios, 2005). Özellikle yoğun monokültür sistemlerinde gelişen yüksek inokulum baskısı göz önüne alındığında, uzun vadeli başarı için entegre yaklaşımlar zorunlu hale gelmektedir.

5.2. Kültürel Mücadele Stratejileri

Kültürel uygulamalar, Fusarium solgunluğu yönetiminin temel bileşenlerinden biridir. Hastalık döngüsünün kırılması açısından en önemli uygulamalardan biri ürün rotasyonudur. Ancak *F. oxysporum*'un geniş konukçu spektrumu ve uzun süreli klamidospor canlılığı nedeniyle kısa süreli rotasyon programlarının çoğu zaman yeterli olmadığı bildirilmektedir. Bu nedenle en az 4–5 yıllık rotasyon programlarının önerildiği çalışmalar bulunmaktadır (Edel-Hermann & Lecomte, 2019). Rotasyon bitkilerinin seçiminde konukçu olmayan türlerin tercih edilmesi büyük önem taşımaktadır.

Toprak solarizasyonu, özellikle sıcak iklim bölgelerinde inokulum yoğunluğunu azaltmak amacıyla kullanılan etkili yöntemlerden biridir. Şeffaf polietilen örtüler kullanılarak toprağın yüksek sıcaklıklara maruz bırakılması, klamidospor canlılığını önemli ölçüde azaltabilmektedir. Solarizasyon uygulamalarının biyolojik mücadele ajanları ile kombine edilmesi durumunda daha yüksek başarı sağlandığı bildirilmektedir (Katan, 2000).

Solarizasyon + Biyolojik Mücadele → İnokulum Baskısında Azalma

Hijyen uygulamaları da epidemiyolojik yönetimde kritik öneme sahiptir. Enfekteli bitki artıklarının üretim alanından uzaklaştırılması, sulama suyu kontaminasyonunun önlenmesi ve tarımsal ekipmanların dezenfeksiyonu, inokulum yayılımını azaltan temel uygulamalar arasında yer almaktadır. Özellikle fide üretim sistemlerinde steril yetiştirme ortamlarının kullanılması ve üretim materyallerinin düzenli olarak test edilmesi gerekmektedir.

Toprak drenajının iyileştirilmesi ve organik madde düzeyinin artırılması da hastalık baskısını azaltabilmektedir. Organik materyal uygulamalarının faydalı mikrobiyal popülasyonları artırarak baskılayıcı toprak oluşumuna katkı sağladığı bildirilmektedir. Ayrıca aşırı azotlu gübreleme uygulamalarının patojen gelişimini teşvik ettiği bilinmektedir. Bu nedenle dengeli gübreleme programları hastalık yönetiminde önemli rol oynamaktadır (Jones vd., 2014).

5.3. Dayanıklı Çeşit Geliştirme ve Sertifikalı Fide Kullanımı

Fusarium solgunluğuna karşı dayanıklı çeşitlerin geliştirilmesi, sürdürülebilir hastalık yönetiminin en etkili stratejilerinden biri olarak kabul edilmektedir. Dayanıklılık mekanizmaları genellikle vasküler kolonizasyonun sınırlandırılması, hızlı savunma yanıtı ve efektör tanıma sistemleri ile ilişkilendirilmektedir. Ancak *F. oxysporum* popülasyonlarının yüksek genetik varyabilite göstermesi, dayanıklılık ıslahını zorlaştırmaktadır (Michielse & Rep, 2009). Moleküler marker destekli seleksiyon teknikleri, dayanıklı genotiplerin belirlenmesinde önemli avantajlar sağlamaktadır. Özellikle genomik çalışmalar sayesinde dayanıklılıkla ilişkili lokusların belirlenmesi, modern ıslah programlarının hızlanmasına katkı sağlamaktadır. Bununla birlikte yeni virülent patotiplerin ortaya çıkabilmesi nedeniyle dayanıklılığın uzun süreli stabilitesi önemli bir araştırma konusu olmaya devam etmektedir.

Sertifikalı fide kullanımı, hastalık yönetiminde kritik öneme sahip uygulamalardan biridir. *F. oxysporum*'un latent enfeksiyon oluşturabilme kapasitesi nedeniyle görsel kontroller çoğu zaman yeterli olmamaktadır. Bu nedenle fide üretim sistemlerinde moleküler tanı tekniklerinin rutin olarak kullanılması önerilmektedir (Henry vd., 2017). Özellikle qPCR tabanlı test sistemleri, latent enfeksiyonların erken dönemde belirlenmesine olanak sağlamaktadır. Fide sertifikasyon sistemlerinde karantina uygulamaları ve düzenli sağlık testleri, patojenin yeni üretim alanlarına taşınmasının önlenmesi açısından stratejik öneme sahiptir. Ayrıca doku kültürü temelli temiz fide üretim sistemleri, başlangıç inokulumunun azaltılmasına katkı sağlamaktadır.

5.4. Biyolojik Mücadele Yaklaşımları

Son yıllarda çevresel sürdürülebilirlik ve fungisit kullanımının azaltılması hedefleri doğrultusunda biyolojik mücadele uygulamaları ön plana çıkmıştır. Özellikle rizosfer mikrobiyomunun hastalık baskılayıcılığı üzerindeki rolünün anlaşılması, biyolojik kontrol ajanlarına olan ilgiyi artırmıştır. *Trichoderma*, *Bacillus*, *Pseudomonas* ve mikorizal funguslar gibi mikroorganizmalar, Fusarium solgunluğuna karşı umut verici biyolojik mücadele ajanları olarak değerlendirilmektedir (Mendes vd., 2011).

Trichoderma türleri, hızlı rizosfer kolonizasyonu, antibiyotik üretimi ve hiperparazitizm kapasitesi sayesinde en yaygın kullanılan fungal antagonistlerden biridir. Bu organizmalar fungal hücre duvarını parçalayan kitinaz ve glukanaz enzimleri salgılayarak doğrudan antagonistik etki gösterebilmektedir. Ayrıca kök gelişimini teşvik ederek bitkinin genel stres toleransını artırdığı bildirilmektedir (Harman vd., 2004). *Bacillus* spp. ve fluoresan *Pseudomonas* türleri ise antibiyotik üretimi, siderofor salgılanması ve niş rekabeti yoluyla patojen gelişimini baskılayabilmektedir. Özellikle siderofor üretimi sayesinde demir rekabeti oluşturarak fungal gelişimi sınırlandırmaktadırlar. Bunun yanında bu bakterilerin bitkide uyarılmış sistemik direnç (ISR) mekanizmalarını aktive ettiği bilinmektedir.

ISR → PR Proteinleri + Fenolik Birikim + Savunma Gen Aktivasyonu

ISR mekanizması kapsamında jasmonik asit (JA) ve etilen (ET) sinyal yolları aktive olmakta, böylece bitki enfeksiyona karşı daha hızlı ve güçlü yanıt verebilmektedir. Bu durum özellikle latent enfeksiyonların baskılanmasında önemli avantaj sağlamaktadır. Bununla birlikte biyolojik mücadele ajanlarının tarla koşullarındaki performansı çevresel faktörlerden önemli ölçüde etkilenmektedir. Toprak sıcaklığı, nem, organik madde düzeyi ve mikrobiyal rekabet gibi faktörler biyolojik ajanların etkinliğini belirlemektedir. Bu nedenle gelecekte mikrobiyal konsorsiyumlar ve sentetik mikrobiyom yaklaşımlarının daha büyük önem kazanacağı düşünülmektedir.

5.5. Kimyasal Mücadelede Sınırlılıklar

Kimyasal fungisitler uzun yıllar Fusarium hastalıklarının yönetiminde temel araç olarak kullanılmıştır. Ancak *F. oxysporum*'un ksilem dokusunda sistemik kolonizasyon gerçekleştirmesi ve toprakta uzun süre canlı kalabilmesi nedeniyle fungisitlerin etkinliği çoğu zaman sınırlı kalmaktadır. Ayrıca sürekli fungisit kullanımı direnç gelişimini teşvik edebilmektedir (Dean vd., 2012).

Kimyasal mücadelede karşılaşılan bir diğer önemli sorun çevresel etkiler ve kalıntı problemleridir. Fungisitlerin toprak mikrobiyotasını olumsuz etkileyerek faydalı mikroorganizmaların baskılanmasına neden olduğu bildirilmektedir. Bu durum uzun vadede toprak baskılayıcılığının azalmasına ve patojen lehine bir rizosfer ortamı oluşmasına yol açabilmektedir. Ayrıca bazı fumigantların çevresel toksisite ve insan sağlığı üzerindeki riskleri nedeniyle kullanımının sınırlandırılması, alternatif yönetim stratejilerine olan ihtiyacı artırmıştır. Özellikle sürdürülebilir tarım sistemlerinde biyolojik ve kültürel uygulamaların kimyasal mücadeleye alternatif olarak değerlendirilmesi ön plana çıkmaktadır.

5.6. Mikrobiyom Tabanlı Gelecek Yaklaşımlar

Modern bitki patolojisi çalışmalarında hastalık yönetimi artık yalnızca patojene odaklanan klasik yaklaşımlardan uzaklaşmakta; bunun yerine bitki–mikrobiyom–çevre etkileşimlerini birlikte ele alan ekolojik modeller ön plana çıkmaktadır. Özellikle baskılayıcı toprak kavramının daha iyi anlaşılması, mikrobiyom mühendisliği çalışmalarına hız kazandırmıştır.

Metagenomik analizler, Fusarium baskılayıcı topraklarda yüksek mikrobiyal çeşitlilik ve fonksiyonel redundans bulunduğunu göstermektedir. Bu durum faydalı mikrobiyal toplulukların birlikte çalışarak patojen baskısını azalttığını düşündürmektedir (Mendes vd., 2011). Gelecekte sentetik mikrobiyal konsorsiyumların geliştirilmesiyle daha stabil biyolojik mücadele sistemlerinin oluşturulması hedeflenmektedir.

İklim değişikliği koşullarında hastalık yönetiminin başarısı, yalnızca patojen baskılanmasına değil aynı zamanda toprak ekosisteminin dayanıklılığının korunmasına bağlı olacaktır. Bu nedenle sürdürülebilir çilek üretim sistemlerinde rejeneratif tarım uygulamaları, organik madde yönetimi ve mikrobiyom destekli stratejiler giderek daha stratejik hale gelmektedir. Sonuç olarak, *F.*

oxysporum kaynaklı vasküler solgunluk hastalığının etkin yönetimi; kültürel uygulamalar, dayanıklı çeşit kullanımı, sertifikalı fide sistemleri, biyolojik mücadele, moleküler erken teşhis yöntemleri ve sürdürülebilir tarım uygulamalarının birlikte kullanıldığı çok katmanlı bir entegre hastalık yönetimi yaklaşımını gerektirmektedir.

6. Sonuç

Fusarium oxysporum f. sp. fragariae, çilek üretim sistemlerinde önemli ekonomik kayıplara neden olan, yüksek adaptasyon yeteneğine sahip vasküler bir fungal patojendir. Patojenin uzun süre toprakta canlı kalabilmesi, latent enfeksiyon oluşturabilmesi ve ksilem dokusunda sistemik kolonizasyon gerçekleştirmesi, hastalığın yönetimini zorlaştıran temel faktörlerdir. Ayrıca iklim değişikliği, artan sıcaklıklar ve yoğun monokültür uygulamaları, Fusarium solgunluğunun gelecekte daha büyük bir epidemiyolojik tehdit oluşturabileceğini göstermektedir. Bu derleme, hastalık gelişiminin yalnızca patojen varlığı ile değil; konukçu fizyolojisi, çevresel koşullar ve toprak mikrobiyomu arasındaki karmaşık etkileşimlerle şekillendiğini ortaya koymaktadır. Özellikle baskılayıcı toprak mikrobiyotasının korunması ve faydalı mikroorganizmaların desteklenmesi, sürdürülebilir hastalık yönetimi açısından kritik öneme sahip olduğunu vurgulamatadır.

Hastalığın etkin yönetimi için tek yönlü mücadele stratejileri yerine; dayanıklı çeşit kullanımı, sertifikalı fide üretimi, biyolojik mücadele ajanları, kültürel önlemler ve moleküler erken teşhis sistemlerini kapsayan entegre hastalık yönetimi yaklaşımlarının birlikte uygulanması gerekmektedir. Ayrıca gelecekte yapılacak çalışmaların, iklim değişikliğinin hastalık epidemiyolojisine etkileri ile mikrobiyom temelli biyolojik mücadele stratejilerine odaklanması önem taşımaktadır. Çilekte, Fusarium solgunluğunun sürdürülebilir şekilde yönetilebilmesi; çevre dostu uygulamaların yaygınlaştırılması, toprak sağlığının korunması ve entegre hastalık yönetimi stratejilerinin üretim sistemlerine etkin şekilde adapte edilmesi ile mümkün olacaktır.

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ANALYSIS OF GEN Z BEHAVIORS IN SUSTAINABLE FASHION CONSUMPTION

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ABSTRACT

The fashion industry is considered one of the sectors with the highest environmental impact due to its high production volume and consumption-oriented structure. In this context, the concept of sustainable fashion has gained increasing importance in promoting environmentally friendly production processes and encouraging more conscious consumption habits. Generation Z (Gen Z), who grew up in the digital age and show a high level of environmental awareness, has emerged as a significant consumer group in terms of sustainable fashion consumption.

The aim of this study is to analyze the attitudes, awareness levels, and purchasing behaviors of Gen Z consumers toward sustainable fashion products. Within the scope of the research, the concept of sustainable fashion is examined in relation to young consumers' environmental awareness and fashion consumption habits. The study evaluates Gen Z individuals' perceptions of sustainable fashion products, their purchasing motivations, and the factors influencing these processes.

The findings of the study indicate that Gen Z consumers have a certain level of awareness regarding sustainable fashion and generally display positive attitudes toward environmentally friendly products. However, factors such as price, brand reliability, environmental impact of the product, and social media influence play a significant role in sustainable fashion consumption.

In conclusion, the environmental sensitivity of Generation Z represents an important potential for the future of the fashion industry. Considering the expectations and consumption tendencies of young consumers while developing sustainable production strategies can contribute to supporting the sustainable transformation of the fashion sector.

Keywords: Sustainable fashion, Generation Z, fashion consumption, sustainable consumption

1. Introduction

The fashion industry is considered one of the sectors with the highest environmental impact on a global scale. Fast fashion production, increasing consumption habits, and textile waste have placed sustainability at the center of the fashion industry.

The issue of sustainability is constantly encountered in our daily lives. As the most popular subject in the marketing communications of famous brands, both didactic discourses and products produced and offered by companies in sustainable categories stand out in advertisements. In particular, the efforts of leading companies in the textile sector, competing with each other, make the issue current and lead to sustainable clothing becoming more prevalent in our lives.

The concept of sustainable fashion first emerged in the 1960s when consumers began to realize the environmental impact of clothing production and thus demanded that the clothing industry change its practices (Jung and Jin, 2014).

Sustainable fashion generally refers to production and consumption processes that adopt environmental, social, and economic sustainability principles.

Within this approach:

- Use of environmentally friendly materials
- Ethical production conditions
- Recycling and reuse
- Circular production models stand out as important elements.

Garment industry, sustainability is achieved by using local resources in the design, manufacturing, and distribution processes of products, preferring transparent production systems with less intermediary between producer and consumer, and producing sustainable products with a longer lifespan (Clark, 2008: 429). Sustainable fashion, while a concept developed in recent years and often used interchangeably with eco, green, and ethical fashion (Carey and Cervellon, 2014: 485), primarily proposes replacing harmful chemicals with environmentally friendly materials and reducing waste and resource consumption through garment recycling. Slow production, a new sustainability movement in the industry, does not utilize natural resources to increase production speed like fast production techniques, and slow consumption requires a longer product lifespan from production to post-consumption (Jung and Jin 2014: 510; Joergens, 2006; Henninger, 2015).

The fashion industry, as a process that continues with the production of products and their acceptance by customers, has led brands to commercialize the concept of sustainability. While the fashion sector tries to attract customers with the concept of sustainability, it also takes a position that encourages consumers to adopt sustainable consumption. In this sense, fashion industry producers can position themselves as important units that can persuade and encourage their customers towards sustainable consumption.

For the sustainable fashion trend to have high consumer preference, companies must first and foremost be transparent in both the supply chain, from raw material procurement to production and branding stages. At the same time, companies are expected to consider pricing policies that support sustainability. Because these factors are highly influential in guiding already complex purchasing intentions.

The impact of human behavior on ecological problems is undeniable. Many of the environmental problems we face today are a direct result of human behavior, and behavioral solutions are needed to take responsibility for this (Oskamp, 2000: 496; Pookulangara and Shepard, 2013). Numerous studies show that consumers are becoming more sensitive and environmentally friendly. In their study, Shetzer, Stackman, and Moore (1991) found that consumers exhibited more sensitive and attentive behavior towards environmental issues.

The overconsumption of natural resources is causing the rapid depletion of traditional sources of many materials. Today, an increasing number of consumers are taking responsibility for changing their personal consumption habits in the hope of solving environmental problems, showing a trend where product choices, usage, and disposal decisions are motivated by environmental protection. With the increase in environmental awareness, consumers are striving to minimize their carbon footprints, and as a result, sustainability is becoming an increasingly accepted concept.

In recent years, the increased environmental awareness of Gen Z (Generation Z) consumers has created a new research area regarding sustainable fashion consumption. Gen Z individuals, born between 1997 and 2012, grew up with digital technologies and are considered a more sensitive consumer group in terms of social responsibility and environmental awareness compared to previous generations. In this context, the aim of this study is to analyze Gen Z consumers' awareness, attitudes, purchasing behaviors, and decision-making processes regarding sustainable fashion products.

2. Consumption Characteristics of Generation Z

Studies in the fields of fashion and sustainable consumption show that young consumers are increasingly paying attention to environmental issues.

Research in the literature reveals:

- Young consumers are developing positive attitudes towards sustainable brands
- However, the price factor can limit purchasing behavior
- Social media is increasing awareness of sustainable fashion.

In addition, second-hand fashion, recycled textiles, and the slow fashion movement are becoming widespread, especially among young consumers.

When the aforementioned characteristics are examined, it is seen that this group tends to coexist with contradictions, which are characteristic of postmodern society. Therefore, it is thought that they are confused, and their consumption habits and other characteristics are formed within this framework. It is particularly important to examine the consumption trends of this generation, which will undertake important tasks in shaping and sustaining social life in future generations, and to make various assessments in this direction. It is known that excessive and unconscious consumption creates numerous social, economic, political, and ecological problems (Lu, Chang and Chang 2015; Straus and Howe, 1991).

This generation, called Gen Z, is a generation that grew up in the digital environment and has quick access to information. The following characteristics stand out in the consumption behavior of this generation:

- Awareness of social and environmental responsibility

- Emphasis on brand transparency
- Openness to the influence of social media
- Interest in personalized products
- Sensitivity to ethical production processes

These characteristics can influence the demand for sustainable fashion products.

In short, understanding consumer behavior and characteristics in the context of sustainability, circular economy, and digital development is crucial for guiding change in the fashion industry.

3. Method

The main objective of this research is to analyze the behavior of Gen Z consumers towards sustainable fashion products and to reveal their consumption trends in this area.

The research seeks answers to the following questions:

1. What is the level of awareness of Gen Z consumers regarding sustainable fashion?
2. What are their motivations for purchasing sustainable fashion products?
3. How do price, brand image, and social media affect sustainable fashion consumption?

At the same time, this study aims to provide important data for fashion brands to develop sustainable product strategies.

A quantitative research method was used in the study. The research model was designed to measure the attitudes and behaviors of Gen Z consumers regarding sustainable fashion consumption.

The population of the research consists of individuals belonging to the Gen Z generation.

Sample group:

- Selected from university students aged 18-25.

Data were collected through face-to-face interviews as part of the course. In the interview, students were asked three main questions and a supporting set of questions regarding:

- Awareness of sustainable fashion
- The impact of sustainable fashion on purchasing behavior
- How price, brand image, and social media affect sustainable fashion consumption.

4. Results

Based on the data collected from students within the scope of the research, four main themes were determined. These are:

- High awareness
- Low purchasing behavior
- Price barrier
- Social media influence

Theme 1: Sustainability Awareness

- 82% of participants consider sustainable fashion important.
- 76% stated that the fashion industry harms the environment.

Example statement:

“I know it harms the environment, but I can’t always shop accordingly.”

- Comment:

→ Awareness is at a high level.

Theme 2: Purchasing Behavior

- Only 34% of students stated that they regularly purchase sustainable products.
- 49% stated that they purchase them “rarely”.
- Comment:

→ There is a significant difference between awareness and behavior.

Theme 3: Price Perception

- 71% of students find sustainable products expensive.
- 64% stated that they do not prefer them due to price.

Example statement:

“Sustainable products are nice, but they are not within my budget.”

- Comment:

→ Price is the strongest deterrent.

Theme 4: Social Media Influence

- 67% of students obtain information about sustainable fashion from social media.
- 52% stated that influencers are influential.
- Comment:

→ Social media plays a critical role in raising awareness.

Attitude – Behavior Comparison

- Awareness: high (82%)
- Behavior: low (34%)
- Result:

→ A significant “attitude-behavior gap” exists. In this context:

- Gen Z is conscious about sustainability.
- However, economic realities limit behavior.
- Social media creates awareness, but it is not sufficient on its own.

According to research findings, a significant portion of Gen Z consumers are aware of sustainable fashion. However, the key factors influencing purchasing behavior are:

- Product price
- Brand reliability
- Environmental friendliness of the product
- Social media influence

The research also shows that young consumers tend to turn to alternative products when sustainable fashion products are expensive. In other words, the price factor positively influences consumers in their preference for sustainable products.

In conclusion, understanding individuals' consumption patterns and making various predictions requires evaluating individuals according to the characteristics of their generation, enabling companies to develop more accurate strategies for their target audience. Individuals' internet usage habits should also be considered when determining these strategies. In an increasingly competitive environment, companies that want to enter the market, stay in the market, and achieve their growth

targets must accurately identify their target audience and develop new strategies by knowing and understanding them.

5. Conclusion

It is observed that a significant portion of young people, referred to as Generation Z, are conscious consumers. The study concluded that a large number of young people included in the research are knowledgeable about sustainable fashion and their awareness reflects this. It is seen that Generation Z young people, who are conscious about sustainable fashion, shape their shopping preferences accordingly. In this context, it can be said that young consumers are in a very good position in terms of ethical consumption, socially responsible consumption, and simple consumption; however, they are in a middle position in terms of environmentally conscious consumption. Overall:

- Generation Z has a high level of awareness regarding sustainability.
- Social media is a supporting factor in their behavior.
- Sustainable fashion is an important value for Gen Z.
- However, this value is not fully reflected in their purchasing behavior.
- The most important obstacles are:

- Price
- Accessibility

Although Generation Z is perceived by society as a consumer generation, it is necessary to emphasize their conscious consumer aspects due to their questioning, researching, quality and reliability-seeking, rights-aware and assertive, ethical, and environmentally conscious characteristics. Furthermore, it is believed that discussions on this generation's consumption trends should focus on conscious consumption trends, contributing to their ability to think and behave accordingly. In this context, it is considered beneficial to evaluate the impact of psychological characteristics such as perception, attitude, and motivation on conscious consumption in future studies. Moreover, it would be meaningful to conduct similar studies using different personality scales on different demographic structures. Finally, it is considered beneficial to develop various projects aimed at educating the younger generation, particularly Generation Z, on conscious consumption, which has a significant impact on the future of societies.

The study results reveal that Generation Z has a positive attitude towards sustainable fashion. However, some strategies need to be developed to promote the widespread adoption of sustainable products. In this context, some suggestions have been developed below:

- Increasing the affordability of sustainable products
- Sharing transparent production processes
- Spreading awareness of sustainable fashion through social media
- Supporting recycling and second-hand fashion platforms

In conclusion, developing sustainability strategies in line with the expectations of Gen Z consumers will provide fashion brands with a significant competitive advantage in the sector.

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DIGITAL COLLABORATION TOOLS AND STUDENT ENGAGEMENT IN GROUP PROJECTS

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ABSTRACT

The integration of digital collaboration tools in higher education has significantly reshaped group-based learning by offering students platforms to communicate, coordinate, and exchange knowledge efficiently. Applications such as Microsoft Teams, Google Workspace, eTwinning, DigitalEdu support both synchronous and asynchronous interactions, creating collaborative environments that go beyond the limitations of traditional in-person group work. This research explores how digital collaboration tools influence student engagement in group projects, emphasizing cognitive, emotional, and behavioural aspects.

These tools promote cognitive engagement by helping students organize ideas, plan tasks, and track project progress through visual aids or shared documents. Emotional engagement is fostered through interactive features that facilitate peer feedback, recognition, and a sense of inclusion, reducing isolation in online or hybrid learning settings. Behavioural engagement is reinforced via transparent tracking of contributions, clearly defined roles, and real-time updates, which encourage accountability and active participation. Together, these features support consistent involvement and enhance overall team performance.

The study used a descriptive research approach, gathering information via student questionnaires and monitoring group activities on digital collaboration platforms. This method enabled the collection of insights into students' perceived engagement, participation patterns, and experiences with the tools, offering a comprehensive understanding of their impact on learning outcomes.

Research evidence shows that structured deployment of digital collaboration platforms enhances student motivation, satisfaction, and learning outcomes. Nevertheless, challenges such as unequal access to technology, potential cognitive overload from excessive notifications, and the need for guidance in managing group interactions must be addressed. Implementing strategies like defined workflows, regular feedback, and reflective exercises can help overcome these issues and maximize engagement.

The novelty of this study lies in its integrated evaluation of multiple engagement dimensions across diverse digital platforms and its emphasis on actionable pedagogical strategies. It highlights how structured workflows, regular feedback, and reflective practices can maximize engagement and learning outcomes, addressing challenges such as unequal access to technology and cognitive overload.

Keywords: Digital Collaboration Tools, Student Engagement, Group Projects, Active Learning, Online Learning Platforms, Collaborative Learning

Introduction

In the context of the accelerated digital transformation that characterizes contemporary society, higher education systems are undergoing profound changes driven by the evolution of information technologies and the need to adapt to the requirements of a knowledge-based economy. Educational institutions can no longer rely exclusively on traditional teaching models centred on the one-way transmission of information; instead, they are required to adopt innovative approaches that leverage the potential of digital technologies. In this regard, the integration of digital collaboration tools into the educational process has become an essential direction, contributing to the development of interactive, flexible, and student-centred learning environments.

One of the fundamental components of modern learning is represented by group projects, which promote collaboration, critical thinking, problem-solving and the development of social competencies. These activities are considered essential for preparing students for integration into the labour market, where the ability to work effectively in teams is increasingly valued. However, the organization and implementation of group projects may encounter significant difficulties, especially in online or hybrid educational contexts where direct interaction is limited. Issues such as lack of coordination, unequal distribution of tasks, or poor communication can negatively affect both the quality of outcomes and the level of student engagement.

In this context, digital collaboration tools such as Microsoft Teams, Google Workspace, eTwinning, DigitalEdu provide effective solutions for overcoming these challenges. These platforms allow not only real-time communication but also task management, document sharing, progress monitoring, and facilitation of feedback among team members. By combining synchronous and asynchronous functionalities, they create a favourable framework for continuous collaboration, regardless of participants' location. Thus, the working process becomes more transparent, organized, and accessible, contributing to increased efficiency in group activities.

A central aspect in evaluating the effectiveness of these tools is their impact on student engagement. The concept of engagement is complex and multidimensional, encompassing cognitive, emotional, and behavioural dimensions. Cognitive engagement refers to the level of intellectual effort invested by students in the learning process, as well as their ability to analyse, synthesize and apply information. Digital tools can support this dimension by facilitating idea organization, content structuring, and progress visualization, for example through Kanban boards or collaborative documents.

The emotional dimension of engagement refers to students' attitudes, feelings, and affective reactions toward learning activities and their peers. In digital environments, maintaining emotional connection can be challenging; however, interactive functionalities such as reactions, comments, and instant feedback can foster a sense of belonging and inclusion. This is particularly important in online or hybrid settings, where the risk of isolation is higher.

Behavioural engagement reflects the level of active participation of students in group activities, including contribution frequency, deadline compliance, and responsibility sharing. Digital collaboration tools facilitate this dimension by providing clear mechanisms for activity tracking, role assignment, and real-time updates. As a result, students become more accountable and more motivated to actively contribute to shared tasks.

Despite these evident benefits, the use of digital collaboration tools is not without challenges. Unequal access to technology may create disparities among students, affecting participation and performance. Additionally, information overload caused by frequent notifications or simultaneous use of multiple platforms can lead to cognitive fatigue and reduced efficiency. Furthermore, the lack of adequate digital competencies or clear pedagogical guidance may limit the potential of these tools.

Therefore, effective integration of digital collaboration tools requires a strategic approach that includes the definition of clear workflows, communication rules, and continuous feedback provision. Reflective practices, which encourage students to analyse their own learning and collaboration processes, can further enhance engagement and improve outcomes. In this regard, the role of the instructor becomes essential not only as a facilitator of learning but also as a guide in the effective use of digital technologies.

Considering these aspects, the study aims to conduct an in-depth analysis of the impact of digital collaboration tools on student engagement in group projects. The research integrates cognitive, emotional, and behavioural dimensions of engagement, providing a comprehensive perspective on how these technologies influence the learning experience.

This study is based on a descriptive methodological design, with the main objective of examining how digital collaboration tools influence student engagement in group projects. The choice of this design is justified by the need to capture students' perceptions, experiences, and behaviours in real learning contexts, without experimental manipulation of variables.

The descriptive approach allows for the investigation of the phenomenon in an authentic setting, offering an overview of the use of digital tools and their impact on the cognitive, emotional, and behavioural dimensions of student engagement. At the same time, the research integrates both quantitative and qualitative elements, ensuring a comprehensive analysis of the collected data.

The main aim of the study is to evaluate the impact of digital collaboration tools on student engagement in group projects. Accordingly, the following specific objectives were formulated:

- to identify how digital tools influence students' cognitive engagement;
- to analyse the effects of these tools on emotional engagement in group activities;
- to assess the level of behavioural engagement facilitated by digital platforms;
- to identify the main challenges associated with the use of digital collaboration tools;
- to formulate pedagogical recommendations for optimizing their use.

Based on these objectives, the research seeks to answer the following questions:

1. To what extent do digital collaboration tools contribute to increasing students' cognitive engagement?
2. How do these tools influence emotional engagement in group projects?
3. What is their impact on behavioural engagement and active participation?
4. What difficulties do students encounter when using these platforms?
5. What strategies can be implemented to maximize their effectiveness?

Chapter 1 highlights that the digital transformation of higher education is leading to a paradigm shift toward student-centred educational models, where collaborative learning becomes essential for developing 21st-century skills. In this context, digital collaboration tools are conceptualized not

merely as technological support systems, but as active factors shaping the learning process by facilitating communication, organization, and content co-creation in group projects. The theoretical analysis emphasizes the multidimensional nature of student engagement—cognitive, emotional, and behavioural—and shows how these tools can support each dimension, thereby enhancing performance and motivation. At the same time, challenges such as unequal access to technology, cognitive overload, and the need for digital skills development are identified, requiring well-structured pedagogical strategies. Overall, the chapter establishes a conceptual framework supporting the idea that effective integration of digital tools, combined with appropriate teaching practices, can significantly enhance collaborative learning experiences.

Chapter 2 of the research aims to investigate how digital collaboration tools influence student engagement in group projects. This stage of the study seeks to validate the formulated hypotheses and provide an applied perspective on the analysed phenomenon through the collection and interpretation of data derived from students' real experiences.

The analysis conducted in this study highlights the essential role of digital collaboration tools in transforming the educational process, particularly in the context of group projects in higher education. Both the theoretical foundation and the empirical results confirm that these tools significantly contribute to increasing student engagement, simultaneously supporting the cognitive, emotional, and behavioural dimensions of learning.

Chapter 1. Theoretical Foundation and Conceptual Framework for the Use of Digital Collaboration Tools in Higher Education

The digital transformation represents one of the most influential processes shaping contemporary society, directly affecting all areas of activity, including education (Selwyn, 2016. In higher education, this transformation goes beyond the mere integration of technologies into teaching practices and involves a profound rethinking of pedagogical paradigms, the roles of educational actors, and the way learning experiences are constructed (Redecker & Punie, 2017). Thus, the shift from a traditional model centred on the teacher and the one-way transmission of knowledge to a student-centred approach focused on competency development has become a strategic priority for academic institutions.

In this context, collaborative learning has gained significant importance, being recognized as an effective approach for developing essential twenty-first-century skills such as critical thinking, communication, creativity, and teamwork. Group projects, as a concrete form of implementing collaborative learning, offer students the opportunity to interact, negotiate meanings, and construct knowledge collectively. However, the effectiveness of these activities largely depends on how they are organized and supported, especially in the context of the expansion of online and hybrid learning environments (Hrastinski, 2008).

The emergence and development of digital collaboration tools have created the conditions for overcoming the limitations of traditional collaboration, offering flexible and scalable solutions for managing group activities (Al-Samarraie & Saeed, 2018). These tools facilitate not only communication but also coordination, monitoring, and evaluation of both individual and collective

contributions, thereby contributing to the creation of more efficient and inclusive learning environments (Garrison et al., 2010).

Digital collaboration tools can be defined as software applications that allow users to work together synchronously or asynchronously, regardless of geographical location, through functionalities such as communication, resource sharing, task management, and co-creation of content (Hrastinski, 2008). These include a wide range of platforms, from messaging and video conferencing applications to complex project management systems and virtual collaborative workspaces.

The essential characteristics of these tools include accessibility, interoperability, ease of use, and the ability to integrate with other educational technologies. They also support different types of interaction, from real-time (synchronous) communication to delayed (asynchronous) collaboration, making them adaptable to diverse learning styles and educational contexts (Hrastinski, 2008). From a pedagogical perspective, digital collaboration tools should not be viewed merely as technological support systems, but as environments that actively shape the learning process, influencing how students interact, distribute responsibilities, and construct knowledge.

Student engagement is a central construct in educational research and is considered a strong predictor of academic success. Literature identifies its multidimensional nature, consisting of cognitive, emotional, and behavioral components (Fredricks & McColskey, 2012; Henrie et al., 2015). Cognitive engagement refers to the level of intellectual effort and learning strategies used by students to understand and process information. Within digital collaborative environments, this dimension is supported by tools that facilitate information organization, access to resources, and activity structuring, such as shared documents and visual planning boards.

Emotional engagement refers to students' affective reactions toward learning activities, peers, and the educational environment (Kahu, 2013). In digital contexts, maintaining emotional connection can be challenging due to the lack of face-to-face interaction. However, interactive functionalities such as comments, reactions, and instant feedback can help foster a sense of belonging and inclusion (Martin & Bolliger, 2018), which is particularly important in online and hybrid learning settings.

Behavioural engagement reflects students' active participation in educational activities, including contribution frequency, adherence to deadlines, and collaboration within groups. Digital collaboration tools support this dimension by providing transparent mechanisms for tracking activities, assigning roles, and updating progress in real time, thereby increasing accountability and participation.

The integration of digital collaboration tools into group projects has the potential to fundamentally transform how students learn and collaborate. These tools enable better organization of activities, more efficient communication, and more structured coordination of tasks, contributing to reduced conflict and increased group cohesion. A major advantage is their ability to provide visibility into the work process, allowing both students and instructors to monitor progress and identify potential issues early. Additionally, they facilitate continuous feedback, which is essential for improving performance and maintaining motivation.

Despite these advantages, the use of digital collaboration tools in education is not without challenges. Unequal access to technology may lead to disparities in participation and performance. Cognitive overload, caused by managing multiple platforms and frequent notifications, can negatively affect concentration and learning efficiency. Furthermore, insufficient digital skills or lack of pedagogical guidance may limit the effective use of these tools, reducing their potential educational impact (OECD, 2015).

To fully leverage the potential of digital collaboration tools, appropriate pedagogical strategies must be adopted. These include clear learning objectives, structured activities, and well-defined collaboration rules. The implementation of clear workflows can improve group organization and reduce ambiguity in task distribution. Regular and constructive feedback is also essential for maintaining student engagement and improving academic performance. Reflective practices that encourage students to analyse their own learning and collaboration processes can further enhance metacognitive skills and self-regulation abilities, highlighting the important role of instructors as facilitators of both learning and digital competence development.

The analysis of existing literature demonstrates that digital collaboration tools have significant potential to enhance student engagement in group projects by supporting cognitive, emotional, and behavioural dimensions of learning (Henrie et al., 2015). However, their effectiveness depends on how they are integrated into the educational process and on the ability of stakeholders to use them strategically (Al-Samarraie & Saeed, 2018).

Therefore, a holistic approach is required, combining technological integration with appropriate pedagogical practices in order to create meaningful and effective learning experiences. In this context, the present study aims to contribute to a deeper understanding of the role of digital collaboration tools in education and to provide practical recommendations for optimizing their use in group projects.

Chapter 2. Empirical Analysis of the Impact of Digital Collaboration Tools on Student Engagement

The research was conducted on a sample of higher education students involved in group projects that make use of digital collaboration tools. The sample was selected using a non-probability convenience sampling method and consisted of students who had access to platforms such as Microsoft Teams, Google Workspace, Slack, Trello, or Miro.

The participants come from various fields of economic studies, which allows for a diversified analysis of their experiences and perceptions.

Two main methods were used for data collection:

a) Questionnaire

The questionnaire was the primary instrument for collecting quantitative data and was structured into several sections corresponding to the dimensions of student engagement. It included Likert-scale items, closed-ended questions, and open-ended questions designed to capture both perceptions and experiences of the participants.

The questionnaire sections focused on:

- the use of digital collaboration tools;
- cognitive engagement (idea organization, task planning);
- emotional engagement (motivation, sense of belonging);
- behavioural engagement (active participation, deadline compliance);
- difficulties and challenges encountered.

b) Observation of group activities

The observation method was used to analyse students' actual behaviours within digital platforms. It enabled the monitoring of interactions, frequency of contributions, collaboration patterns, and use of platform functionalities.

The observation was non-intrusive and based on naturally occurring student activity, without researcher intervention.

Data collection took place over one academic semester, during which students were involved in group projects using digital collaboration tools. Questionnaires were distributed online, ensuring anonymity and confidentiality of responses.

Participation in the study was voluntary, and students were informed about the research purpose and data usage. In parallel, group activities were monitored on the digital platforms used to collect observational data.

Collected data were analysed using descriptive statistical methods such as frequencies, percentages, and means in order to highlight general trends and response distributions. Comparative analyses were also performed to identify differences between engagement dimensions. Responses to open-ended questions were analysed using a qualitative approach based on thematic analysis, allowing the identification of main categories and response patterns.

The research respected ethical principles specific to academic studies. Participation was voluntary, and respondents could withdraw at any time. All data were anonymized and used exclusively for scientific purposes. Data privacy and confidentiality were strictly ensured.

Although the study provides relevant insights into the impact of digital collaboration tools, several limitations must be considered. The use of a convenience sample limits the generalizability of the findings. Additionally, observation of digital activities does not fully capture students' cognitive and emotional processes, which may affect interpretation of results.

The study was conducted on a sample of 85 students from the Academy of Economic Studies of Moldova, coming from fields such as economics, business administration, information technology, finance, accounting, international economic relations, marketing and logistics, and hospitality services.

Most students (approximately 68%) reported frequent use of digital platforms in academic activities, while 32% indicated moderate or occasional use. The most commonly used platforms were Microsoft Teams and Google Workspace, as well as DigitalEdu and eTwinning, depending on project requirements and team preferences.

The analysed activities took place over one academic semester and included group projects lasting between 2 and 4 weeks, requiring continuous collaboration, task distribution, and joint delivery of outputs.

Cognitive engagement analysis

The results indicate that digital collaboration tools had a significant impact on students' cognitive engagement. Approximately 74% of respondents stated that these tools helped them organize ideas more efficiently and structure project tasks. The use of shared documents and visual boards (such as Kanban boards) facilitated planning and progress monitoring. Students reported that simultaneous access to information and real-time editing contributed to a better understanding of tasks and improved coordination. Furthermore, 69% of participants believed that digital tools stimulated critical thinking and information analysis, particularly through collaborative content development and rapid peer feedback. This highlights the role of technology in supporting complex cognitive processes and promoting active learning. However, around 18% of students reported difficulties related to information overload, stating that the simultaneous use of multiple platforms may create confusion and reduce concentration.

Emotional engagement analysis

Regarding emotional engagement, results show that digital collaboration tools contributed to a more inclusive and motivating working environment. Approximately 71% of respondents reported feeling more connected to their peers due to platform communication features. Functionalities such as chat, comments, and reactions were perceived as important for maintaining constant interaction and expressing opinions. Students particularly valued instant feedback, which increased confidence and motivation. At the same time, 64% of participants stated that these tools reduced feelings of isolation, especially in online or hybrid learning contexts. This confirms the importance of the social dimension of learning and the role of technology in supporting it. However, about 15% of students reported low emotional engagement, citing the lack of face-to-face interaction and difficulties in interpreting tone or intent in written communication.

Behavioural engagement analysis

The analysis of behavioural engagement shows that digital collaboration tools had a positive effect on students' active participation. Approximately 78% of respondents stated that they were more involved in task completion due to the transparency provided by platforms.

Progress tracking and role assignment features increased individual accountability and deadline compliance. Students noted that visibility of each team member's contributions reduced "free-riding" behaviour and encouraged fair participation. Additionally, 72% of participants reported increased participation frequency due to the accessibility and flexibility of digital tools. Asynchronous contribution was considered a major advantage, especially for students with different schedules.

However, around 20% of students reported difficulties in time management and maintaining discipline in the absence of direct supervision.

The analysis highlighted several challenges associated with the use of digital collaboration tools:

- unequal access to technology (22% of respondents);
- cognitive overload caused by notifications and large information volumes (27%);
- lack of digital skills for certain platforms (19%);
- communication and coordination issues in virtual teams (16%).

These findings emphasize the need for a balanced approach to technology integration, taking into account students' needs and capabilities.

Based on the results, the following recommendations can be formulated:

- use a limited number of platforms to reduce overload;
- clearly define roles and responsibilities within teams;
- provide training on the use of digital tools;
- implement regular feedback mechanisms;
- encourage reflection on the collaboration process.

The research results confirm the formulated hypotheses and highlight the positive impact of digital collaboration tools on student engagement in group projects. These tools contribute to improved organization, communication, and participation, supporting all three dimensions of engagement.

However, their effectiveness depends on how they are used and integrated into educational activities. Lack of structure or excessive use of technology may reduce benefits and create difficulties.

The practical part of the research demonstrates that digital collaboration tools represent an important factor in stimulating student engagement in group projects. They offer significant opportunities for improving the learning experience, but their effective use requires a strategic and pedagogically grounded approach.

The obtained results contribute to validating the theoretical framework and provide a solid foundation for the formulation of general conclusions and future research directions.

Recommendations

- ✓ **Structured integration of digital tools into instructional design**

  Teaching staff should plan the use of digital collaboration tools in a coherent manner by establishing clear objectives, well-defined workflows, and explicit collaboration rules in order to avoid fragmented and inefficient use.

- ✓ **Reducing cognitive overload by limiting the number of platforms used**

  It is recommended to use a restricted set of digital tools, selected according to the specific needs of the project, in order to facilitate student adaptation and reduce confusion caused by managing multiple applications simultaneously.

- ✓ **Developing digital competencies of students and academic staff**

  Higher education institutions should provide training sessions and technical support for the effective use of digital platforms, thereby increasing competence levels and ensuring their optimal utilization.

- ✓ **Promoting continuous feedback and reflective practices**

  The integration of regular feedback mechanisms and the encouragement of reflection on the collaboration process can enhance student engagement and support the development of self-regulation skills.

- ✓ **Ensuring equity in access to technological resources**

  Educational institutions must identify and reduce disparities in access to technology by

providing alternative solutions or support for students facing difficulties, ensuring fair participation in group activities.

Conclusions

The use of digital collaboration platforms facilitates information organization, task planning, and progress monitoring, leading to a more structured learning process and the development of critical thinking skills. The emotional dimension is also positively influenced through the creation of an interactive collaborative environment that promotes communication, feedback, and a stronger sense of group belonging. Regarding behavioural engagement, the results indicate that transparency and monitoring functionalities embedded in these tools enhance individual responsibility and active participation.

However, the study also highlights several challenges that may limit the effectiveness of digital collaboration tools. These include unequal access to technology, cognitive overload caused by excessive platform usage, and the need to develop digital competencies among both students and teaching staff. These aspects emphasize the importance of a well-structured pedagogical integration that maximizes the benefits of technology while minimizing its potential negative effects.

In conclusion, digital collaboration tools represent a key factor in modernizing higher education and promoting student-centred educational practices. Their effective use can lead to improved learning quality, higher academic performance, and the development of essential competencies required in contemporary society. Nevertheless, the success of their implementation depends on the adoption of appropriate teaching strategies and on ensuring an inclusive and well-organized educational framework.

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SUSTAINABLE ENGINEERING WASTE-TO-ENERGY (WTE) SOLUTIONS FOR LANDFILL REDUCTION AND URBAN CLIMATE RESILIENCE IN SOUTH ASIA

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ABSTRACT

The rapid urbanization in South Asia has resulted in a high rate of increase in the amount of municipal solid waste (MSW) that has raised serious environmental and climate-related issues. Traditional waste management, including open dumping and landfilling, is among the major sources of greenhouse gases, especially methane, which worsens the effects of climate change. This paper examines sustainable waste-to-energy (WTE) technologies as a combined solution to urban climate resilience in South Asia. The main aim is to assess the technical, environmental, and economic viability of the WTE systems, such as incineration, anaerobic digestion, gasification, and pyrolysis, in the densely populated urban contexts. A comparative evaluation model is created based on life cycle analysis (LCA), energy-saving measures, and reduction of emissions. The results of the analysis of the data obtained in the selected South Asian cities are used to determine the estimates on the waste generation rates, the calorific value, and the potential energy conservation. Results indicate that hybrid (WTE) systems combining anaerobic digestion and thermal conversion can significantly reduce landfill dependency while generating renewable energy. The results show that there could be up to a 60–800% decrease in the number of landfills and a significant percentage decrease in carbon emissions. Moreover, decentralized waste-to-energy (WTE) systems are more adaptable to urban resilience to climatic stress factors, including flooding and extreme heat conditions, as they can be designed to operate independently and provide energy locally, reducing vulnerability to centralized energy supply disruptions. The conclusion of the study is that incorporating waste-to-energy (WTE) technologies into the cities can lead to more beneficial outcomes (such as increased sustainability, minimized risks to the environment, and climate adaptation policies in South Asia). The presence of policy support, technological innovation, and awareness of the population is of great importance in implementation, as these factors can significantly enhance the effectiveness and acceptance of waste-to-energy (WTE) technologies in urban areas facing climatic stress factors. Implementation, as these factors can significantly enhance the effectiveness and acceptance of waste-to-energy (WTE) technologies in urban areas facing climatic stress factors.

Keywords: Waste-to-Energy, Climate Resilience, Municipal Solid Waste, South Asia, Sustainable Engineering, LCA

1.Introduction

Rapid and often unregulated urbanization across South Asia has created a severe challenge in municipal solid waste (MSW) management. As urban populations continue to expand, waste generation has increased significantly, exceeding the handling capacity of conventional disposal systems such as open dumping and landfilling. These traditional methods are not only inefficient but also major contributors to environmental pollution and greenhouse gas emissions. Methane emissions from decomposing organic waste in landfills present a critical concern due to their high global warming potential and long-term impact on climate change [9], [10]. Consequently, there is an urgent need for sustainable and technologically advanced waste management solutions. Waste-to-Energy (WTE) technologies have emerged as a promising approach to address both waste accumulation and energy shortages. Globally, WTE systems have evolved from simple incineration techniques to advanced thermal and biological conversion processes, including gasification, pyrolysis, and anaerobic digestion [13]. These technologies are increasingly recognized as essential tools in industrial environmental management, enabling efficient waste treatment while generating useful energy [8]. In the Asian context, the adoption of WTE technologies is influenced by waste composition, calorific value, and economic feasibility. Studies have highlighted that selecting appropriate WTE technologies is crucial for ensuring optimal performance and sustainability in developing regions [1], [9].

Furthermore, simulation-based assessments have become vital in evaluating the energy recovery potential of urban waste in developing countries. Such approaches enable accurate prediction of system performance and support techno-economic decision-making for large-scale implementation [4]. Case studies from regions such as Jerusalem also demonstrate the practical feasibility of WTE projects in managing municipal waste while producing energy [6]. The integration of WTE systems into urban infrastructure is closely aligned with the concept of a circular economy. The urban nexus framework, which links energy, water, food, and waste (EWFW), provides a comprehensive model for sustainable city development [3]. By converting waste into valuable resources, WTE technologies contribute directly to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) [10]. Additionally, effective WTE implementation plays a significant role in carbon management strategies by reducing landfill emissions and promoting cleaner energy production [5]. From a technological perspective, WTE systems can be broadly categorized into thermal and biological processes. Thermal technologies are suitable for treating inorganic and high-calorific waste, whereas biological methods such as anaerobic digestion are more effective for organic waste streams. Biogas generation has shown significant potential as a renewable energy source, especially in developing regions. Research on commercial biogas systems highlights their effectiveness in decentralized waste management and rural energy supply, offering valuable lessons for countries in South Asia [2], [7]. Despite these

advantages, the implementation of WTE technologies faces several challenges. High initial investment costs, lack of public awareness, and insufficient policy support hinder large-scale deployment. Creating an enabling environment through public private partnerships (PPPs) is essential for overcoming financial barriers and ensuring project sustainability [12]. Moreover, environmental and social considerations must be carefully addressed to gain public acceptance and ensure long-term success of WTE initiatives [11].

Table 1. Previous Work Conducted on Sustainable Waste-To-Energy (WTE) Solutions For Urban Climate Resilience in South Asia

Ref	Aim	Method	Research Findings	Research Gap
[14]	Assess MSW management and WTE adoption Johannesburg	Case study analysis using municipal waste data	WTE reduced landfill waste volume by 35%	Limited scalability analysis for other urban regions
[15]	Evaluate adaptation of WTE technologies globally	Comparative review of global WTE implementation strategies	Energy recovery efficiency improved up to 30%	Lack of region-specific economic feasibility studies
[16]	Compare different WTE implementation approaches globally	Policy and technical comparison across multiple projects	Cost variations observed between projects exceeded 25%	Insufficient integration of social acceptance factors
[17]	Develop integrated solid waste system for smart cities	System modeling combining renewable energy and waste management	Energy generation increased by approximately 20% efficiency	Lack of real-world pilot scale implementation validation
[18]	Analyzing climate change impacts on urban systems globally	Comprehensive assessment using urban climate change datasets	Urban emissions projected increase by 40% globally	Limited focus on WTE as mitigation strategy
[19]	Promote WTE using Nexus thinking and policies	Policy analysis integrating environmental and economic frameworks	Emission reductions achieved up to 25% potential	Lack of practical implementation frameworks in developing countries
[20]	Evaluate WTE best practices across African regions	Comparative case studies of African WTE projects	Waste conversion efficiency reached nearly 28% average	Limited technological adaptation for local waste compositions
[21]	Explore energy-aware intelligence in megacities waste systems	Analytical modeling using smart city energy frameworks	Energy optimization improved system efficiency by 22%	Insufficient integration with decentralized WTE systems
[22]	Assess WTE implementation challenges in Delhi city	Case study analysis of municipal waste systems	Waste processing capacity increased by 32%	Lack of long-term environmental impact assessment studies
[23]	Analyze economic value creation through WTE systems	Economic modeling and cost-benefit analysis approach	Return on investment improved by approximately 18%	Limited inclusion of environmental externalities in analysis

1.1 Problem Statement

The fast urbanization of South Asia has resulted in a significant rise in the production of municipal solid waste (MSW). Due to poor infrastructure, a lack of technological adoption, and ineffective policy execution, nations like Bangladesh, India, Pakistan, and Nepal are facing significant issues in handling this increasing waste volume. Most of the urban trash is still disposed of via unregulated landfilling and open dumping, which greatly increases greenhouse gas emissions, especially methane, and degradation of the environment. In highly populated cities, these activities raise public health hazards in addition to deteriorating the quality of the air, land, and water.

Furthermore, South Asia's highly organic MSW content offers both a difficult and an opportunity. Waste-to-Energy (WTE) technologies present a significant opportunity for energy recovery, even if incorrect treatment causes fast decomposition and emissions. However, the widespread adoption of sustainable waste management technologies is hampered by the absence of integrated systems, inadequate funding, and lax regulatory frameworks. The region's waste management and disposal systems are further complicated by climate-related risks including flooding and very high or low temperatures. The development of effective, scalable, and ecologically friendly WTE systems that are suited to South Asian circumstances is therefore imperative. decreasing reliance on landfills, decreasing the effects of climate change, and enhancing urban resilience all depend on addressing these issues.

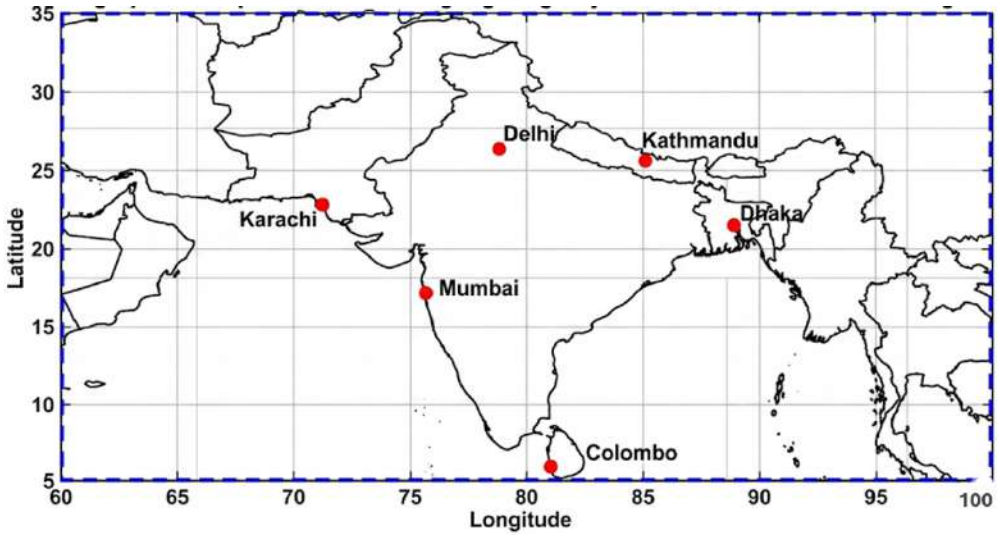


Fig.1. Geographical map of South Asia highlighting major urban waste generation regions.

The proposed research will focus on assessing the technical, environmental, and economic viability of the Waste technologies in South Asia. This study investigates the possible sustainable directions to decrease the reliance on landfills and increase the sustainability of cities, concentrating on hybrid solutions that involve thermal and biological mechanisms. It is hoped that the results will inform effective, climate-resilient waste management approaches to expand urban areas in rapid growth.

2. Methodology

The paper utilizes a combined and sequential approach to assess the technical, environmental, and economic viability of Waste-to-Energy (WTE) systems to improve urban climate resilience in South Asia. The methodology is an intertwining of data gathering, characterization of waste, modeling of technology, life cycle analysis, and economic analysis to guarantee a holistic analysis of Waste implementation in the region-specific circumstances.

2.1 Study Area and Data Collection

The study targets the specific urbanizing cities in South Asia that have been chosen and the generation of municipal solid waste (MSW) has grown tremendously with the growth in population and urban areas. Peer-reviewed journal articles, government publications and international databases were used to gather secondary data. The variables in the dataset are vital, among others, waste production rate, waste composition, moisture content, and calorific value. These variables will be crucial in determining the appropriateness of various Waste technologies. To achieve consistent and reliable data, data preprocessing methods such as normalization and averaging were used. The dataset chosen incorporates common features of urban waste in the developing areas, where the proportion of organic matter is high.

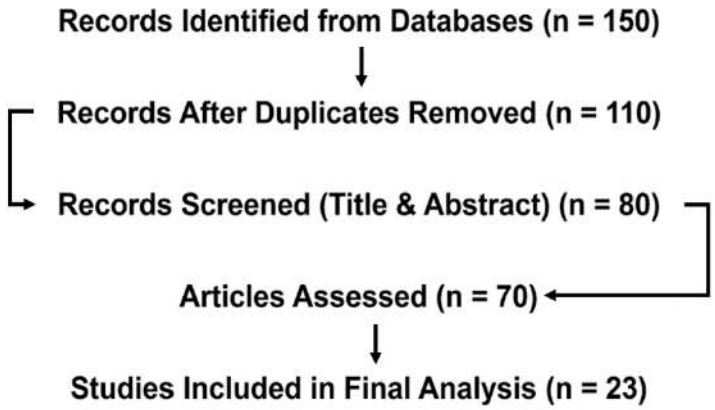


Fig.2. PRISMA flow chart of the data collection and selection of MSW.

2.2 Waste Characterization and Energy Potential Estimation

The composition of waste was carefully analyzed to provide information whether it could be recycled in the form of energy or not. The MSW was sorted into organic, plastic, paper and inert fractions. The moisture content and volatile matter were estimated using proximate analysis methods, and the calorific values were estimated using standard empirical correlations. The conversion efficiency factors of each Waste technology were used to determine the energy potential of the waste. Fractions of organic waste were to be looked at as anaerobic digestion and those fractions that were combustible e.g. plastics and papers were to be used as thermal processes. This step gives a base on evaluating suitable technology directions and approximating the possible energy production.

Table 2. Composition and calorific value analysis of municipal solid waste.

Waste Component	Composition (%)	Moisture Content (%)	Calorific Value (MJ/kg)	Suitable WTE Technology
Organic Waste	50–65	50–60	4–6	Anaerobic Digestion
Plastics	10–20	5–10	30–40	Incineration / Pyrolysis
Paper & Cardboard	8–15	10–20	12–16	Incineration / Gasification
Textiles	2–5	10–15	14–18	Incineration
Glass & Metals	3–7	0–2	~0	Not Suitable (Recycling)
Inert Materials	5–10	5–10	1–3	Landfill / Low-grade Recovery

2.3 Waste-to-energy Technology Modeling and Waste-to-energy Simulation

The analysis and comparison of four main Waste-to-Energy technologies, which include incineration, anaerobic digestion, gasification, and pyrolysis, was conducted. Each technology was evaluated based on factors such as energy efficiency, operational requirements, environmental impact, and adaptability to local waste conditions. A hybrid system combining anaerobic digestion and thermal conversion was also developed to maximize energy recovery and minimize residual waste generation. The modeling approach is based on standard engineering assumptions and performance indicators derived from existing literature. The technology selection criteria include efficiency, scalability, emission levels, and suitability for South Asian waste characteristics.

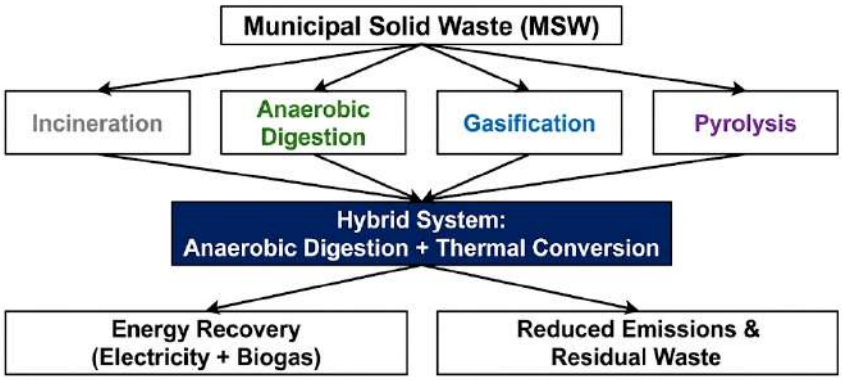


Fig.3. Schematic representation of Waste-to-Energy (WTE) technology modeling and hybrid system integration framework.

2.4 The second method is Life Cycle Assessment (LCA)

The environmental impacts of various Waste technologies were appraised through a Life cycle assessment (LCA) approach. All processes such as waste collection, transportation, processing, energy generation and the ultimate disposal are analyzed. Indicators of environmental quality including greenhouse gas emissions, energy balance, and ecological footprint were measured. The outcomes of the LCA were contrasted with traditional waste

management systems under landfill to emphasize the advantages of Waste technologies on the environment. This analysis gives insight to sustainability and the long-term performance of the environmental performance of every system.

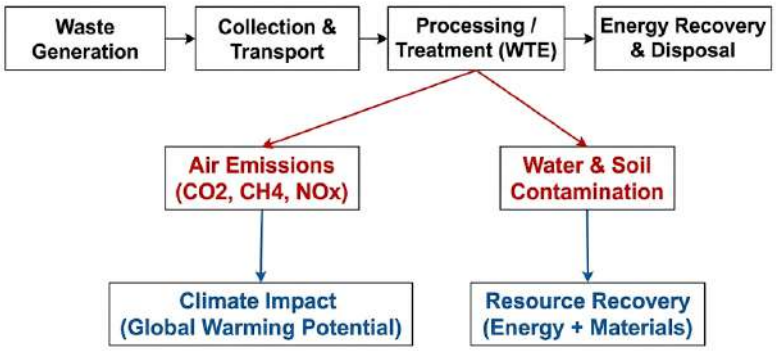


Fig.4. Waste system life cycle stages and the pathways of environmental impact of waste systems.

2.5 Economic Analysis

Economic analysis to ascertain feasibility of WTE implementation was carried out. The analysis entails capital investment, operation and maintenance and the possible revenue that will be generated by energy generation. Economic parameters of net present value (NPV), internal rate of return (IRR), and payback period were estimated to determine the viability of the projects. Further sensitivity analysis was conducted to explore the impact of changes in energy prices, waste supply, and the operation cost. The findings are used to find viable economic solutions that can be adopted in the growth of urban areas.

2.6 Comparative Evaluation and validation

A comparative strategy framework was created to incorporate technical, environmental, and economic results. Multi-criteria decision analysis (MCDA) was used to rank the performance of the various Waste treatment technologies. The hybrid Waste model was confirmed to the relevant data of the chosen cities of South Asia to assert the practical feasibility. The assessment would outline the best options to lessen landfill addiction and improve climate resilience.

Table 3. Comparative Performance and Ranking of Waste-to-Energy (WTE) Technologies.

WTE Technology	Energy Efficiency (%)	Waste Reduction (%)	CO_2 Emission Reduction (%)	Economic Feasibility (NPV/IRR)	Overall Ranking
Incineration	70–85	80–90	40–55	Moderate (IRR 12–15%)	2
Anaerobic Digestion	60–75	50–65	55–70	High (IRR 14–18%)	1
Gasification	65–80	70–85	45–60	Moderate (IRR 11–16%)	3
Pyrolysis	60–78	65–80	50–65	Moderate (IRR 10–15%)	4

Hybrid System	75–90	85–95	60–80	Very High (IRR 15–20%)	1 (Best Overall)

All in all, this methodological framework provides a holistic foundation in the evaluation of sustainable Waste solutions and informing the process of making decisions about the management of urban waste in South Asia.

3. Results and Dıscussıon

3.1 Results

In this study, the findings provide a valuable assessment of Waste-to-Energy (Waste to energy) technologies with respect to technological performance, environmental performance, and cost-effectiveness on urban settings in South Asia. This analysis will be based on processed municipal solid waste (MSW) data, life cycle results and comparison modeling of various Waste systems. The results show the possibility of combinative Waste management methods that can minimize landfill reliance and help to generate renewable energy.

3.1.1 Characteristics and Climate Potential of Municipal Solid Waste

The composition of MSW in the selected South Asian cities show that the ratio of organic waste is the largest (50-65) with plastics, paper, and inert materials coming next (10-20), (8-15): respectively. The mixed waste was determined to have an average calorific value of 6-10 MJ/kg, which is not that high to incinerate directly but can be used in a hybrid system. The level of moisture content (usually 40-55) also promotes the application of biological treatment, including anaerobic digestion. The energy recovery potential of MSW is estimated to be 450-750 kWh per ton depending on the waste makeup and conversion efficiency.

Table 4. Composition and energy recovery in MSW in South Asian cities.

Waste Component	Average Composition (%)	Calorific Value (MJ/kg)	Energy Recovery Potential (kWh/ton)	Suitable WTE Pathway
Organic Waste	50–65	4–7	200–350	Anaerobic Digestion
Plastics	10–20	20–35	600–900	Incineration / Pyrolysis
Paper/Cardboard	8–15	12–18	400–650	Incineration
Textiles	3–8	15–22	450–700	Gasification
Glass & Metals	5–10	0	0	Recycling (non-energy)
Inert Materials	5–12	<1	Negligible	Landfill Disposal
Total MSW Mix	100	6–10 (avg.)	450–750 (avg.)	Hybrid WTE Systems

3.1.2 Performance of WTE Technologies

The comparative analysis of performance of Waste treatment technologies indicates that incineration has the highest volume reduction efficiency (up to 8590 percent) and anaerobic digestion has a better performance in processing organic waste and biogas yield (80120 m 3 /ton). Gasification and pyrolysis have shown moderate efficiencies with enhanced energy recovery capabilities when used on segregated waste streams. Use of hybrid Waste minimization system which involved anaerobic digestion and thermal conversion had a total system efficiency that was about 25-30 percent more efficient than individual systems.

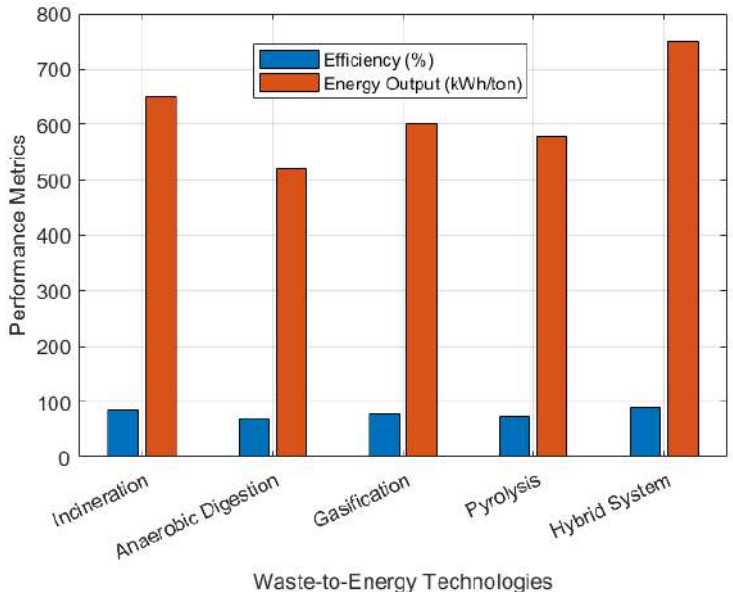


Fig.5. Waste efficiency and output of Waste technologies in comparison.

3.1.3 Environmental Impact Assessment

The findings of the Life Cycle Assessment (LCA) show that WTE technologies considerably decrease the level of greenhouse gas emissions compared to traditional landfill technologies. Based on the technology applied, methane emission has been reduced 40-70 times. The hybrid system exhibits the greatest environmental benefit of integrating reduction of emissions as well as generation of renewable energy. Moreover, thermal processes can lower the volume of waste to a minimum, minimizing the land utilization demands and the environmental pollution risks.

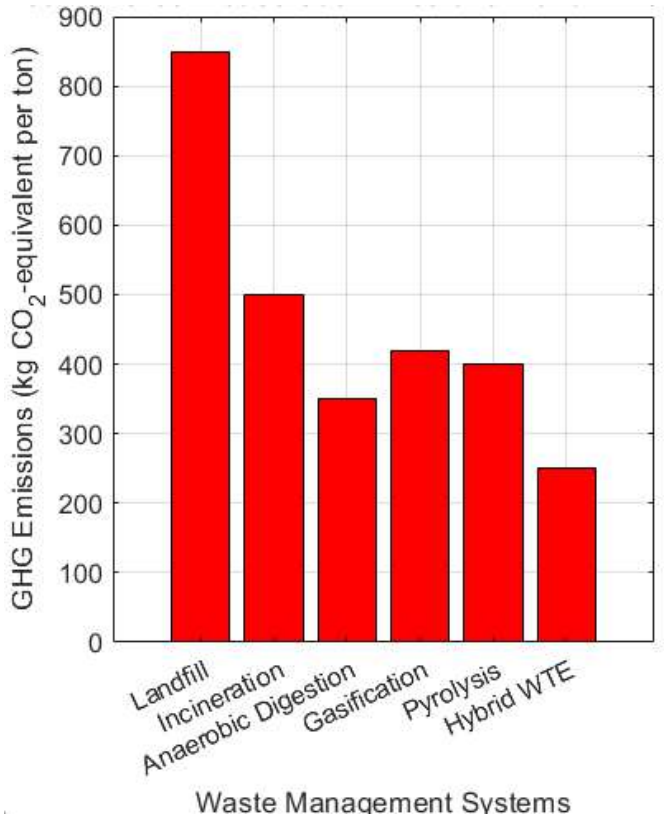


Fig.6. Comparison between landfill and WTE emission of greenhouses gases.

3.1.4 Economic Feasibility Analysis

According to the economic analysis, Waste to Energy systems is rather costly to install, yet provide financial rewards in the long run. The present net value (NPV) of hybrid systems is favorable in moderate energy pricing conditions, and the internal rate of return (IRR) is between 12-18%. It is estimated to take between 6 to 10 years. Electricity generation and carbon credit also generate a lot of revenue which translates to economic viability especially in big city centers.

Table 5. Economic performances indicators of Waste treatment technologies.

WTE Technology	Capital Cost (USD/ton capacity)	Operating Cost (USD/to waste)	Net Present Value (NPV)	Internal Rate of Return (IRR, %)	Payback Period (Years)	Economic Ranking
Incineration	600–900	40–70	Moderate	12–15	7–10	3
Anaerobic Digestion	500–800	30–60	High	14–18	6–9	1
Gasification	700–1100	50–80	Moderate	11–16	8–11	4
Pyrolysis	650–1000	45–75	Moderate	10–15	8–12	5
Hybrid System	800–1200	50–85	Very High	15–20	6–8	1 (Best Overall)

3.1.5 Hybrid Waste Systems Performance

The hybrid Waste model shows a high level of performance on all the evaluation parameters. The decrease in landfill dependency is about 60-80 per cent and energy recovery generation improves much. There is also increased flexibility of the system to fluctuating waste makeup and climate conditions. Decentralized hybrid systems are said to have extra resilience assets especially in flood-prone and densely populated cities, where centralized waste management systems usually experience some difficulties in running.

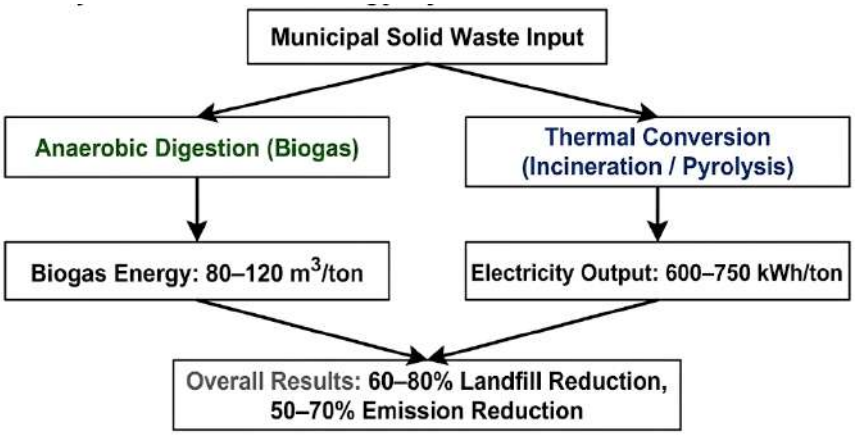


Fig.7. Hybrid Waste system performance model.

3.2 Discussion

3.2.1 Consequences of Waste Management in Urban Areas

The outcomes emphasize how Waste-to-Energy technologies can be a radical contender in urban waste management systems in South Asia. Through waste-to-energy conversion, cities can reduce dependence on landfills and simultaneously address energy deficits. Biological treatment methods are particularly effective due to the high proportion of organic content in municipal solid waste (MSW) in the region. However, these systems must be integrated with thermal technologies to efficiently manage heterogeneous waste streams and ensure complete waste processing in urban environments.

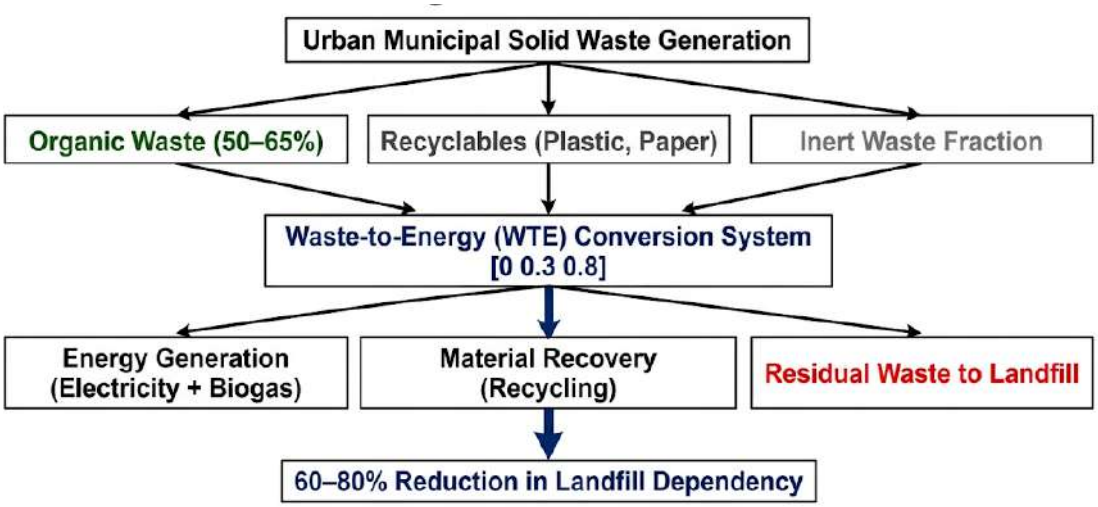


Fig.8. Impact pathway of Waste-to-Energy (WTE) systems on urban municipal solid waste management and landfill reduction.

3.2.2 Strengths of the Environment and Climate

Wastewater treatment systems promote a decrease in methane production and the production of renewable energy, which would contribute to the mitigation of climate change. Hybrid systems improve resource utilization thus increasing the climate response of systems. In addition, decentralized Waste elaborate enhances resilience of cities by maintaining infrastructural sustainability in the face of severe weather like flooding and heatwaves as well.

3.2.3 Economic and Policy Implications

Even though WTE projects are capital-intensive, the result in the long-term economic benefits helps to justify the investment. Implementations require government incentives, subsidies, and public-private partnerships (PPP) to be successful. It needs to be policy frameworks of waste separation, energy pricing provisions, and environmental standards to encourage sustainable WTE implementation.

3.2.4 Limitations and Future Research Directions

Although the results are promising, this study possesses some limitations such as using secondary data and generalized assumptions in the modeling. Future studies would need to be concerned with pilot-scale deployment, real-time monitoring of performance and incorporation of smart technologies to promote optimized waste management. Moreover, the socio-economic aspects and acceptance by a population need to be studied further to make sure that WTE systems are adopted on a large scale.

4.Conclusıon

This paper illustrates how sustainable Waste-to-Energy (Waste to energy) technologies can be used as an effective solution to the increasingly high levels of municipal solid waste in South Asia and improve the resilience of urban climates. The findings confirm that hybrid WTE systems integrating anaerobic digestion and thermal processes significantly improve energy recovery and reduce landfill dependency by up to 60–80%. Environmental analysis shows that the levels of greenhouse gas reduction, especially that of methane, are high as opposed to the traditional methods of waste disposal. Economic analysis shows that under favorable policy environment, WEST projects are economically feasible, especially over the long term although their initial costs are high. In general, decentralized WTE systems and hybrid ones can be integrated with emerging urbanism supporting sustainable urban development. Large-scale implementation that cuts across the rapidly urbanizing regions needs strong government policies, public awareness and technological innovation to be successful.

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EVALUATION OF THE UTILIZATION POTENTIAL OF NUTRIENT-RICH COLD-PRESSED BLACK CUMIN (*NIGELLA SATIVA* L.) SEED CAKE IN MODEL FOODS

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ABSTRACT

With the growing emphasis on sustainability and waste reduction in food production, increasing attention has been directed toward the nutritional valorization of plant-based press cakes generated during oilseed processing. Black cumin (*Nigella sativa* L.) press cake, obtained after oil extraction by cold pressing, is a valuable by-product due to its high protein, dietary fiber, and bioactive compound content. However, studies addressing its direct use in human nutrition and providing a comprehensive evaluation of its nutritional value remain limited. Current findings indicate that black cumin press cake has the potential to enhance the nutritional profile of food products as a plant-based source of protein and dietary fiber. In addition, it may contribute significantly to antioxidant capacity due to its phenolic compound content. Nevertheless, its characteristic aromatic profile, slightly bitter taste, and dark color may limit consumer acceptance, particularly in light-colored food products. Therefore, determining appropriate levels of incorporation and processing strategies is essential for its successful application in food formulations. In this study, three different model food products, namely a yogurt topping powder, an oat–black cumin bar, and crackers, were developed to evaluate the utilization potential of black cumin press cake. Sensory evaluations revealed that varying incorporation levels influenced aroma, color, and overall acceptability, while acceptable sensory properties could be achieved through appropriate formulation strategies. In conclusion, cold-pressed black cumin press cake can be considered not only as a by-product but also as a promising alternative ingredient with high nutritional value and functional properties when properly formulated. This study provides an applied perspective on the use of black cumin press cake within sustainable food systems.

Keywords: BC-Cake, Nutritional value, Plant-based protein, Dietary fiber, Functional food applications.

BESLEYİCİ ÖZELLİKLERE SAHİP SOĞUK PRES ÇÖREK OTU KÜSPESİNİN MODEL GIDALARDA KULLANIM POTANSİYELİNİN DEĞERLENDİRİLMESİ

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ÖZET

Gıda üretiminde sürdürülebilirlik ve atık azaltma yaklaşımlarının önem kazanmasıyla birlikte, yağlı tohum işleme süreçleri sonucunda ortaya çıkan bitkisel küspelerin beslenme açısından değerlendirilmesine yönelik çalışmalar artış göstermektedir. Soğuk pres yöntemiyle yağ üretimi sonrası elde edilen çörek otu (*Nigella sativa* L.) küspesi, yüksek protein, diyet lifi ve biyoaktif bileşen içeriği ile dikkat çeken önemli bir yan üründür. Ancak bu küspenin doğrudan insan beslenmesinde kullanımına ve besin değerinin bütüncül olarak değerlendirilmesine yönelik çalışmalar sınırlıdır. Mevcut bulgular, çörek otu küspesinin bitkisel protein ve lif kaynağı olarak ürünlerin besinsel profilini geliştirme potansiyeline sahip olduğunu göstermektedir. Ayrıca içerdiği fenolik bileşikler sayesinde antioksidan kapasite açısından da önemli bir katkı sağlayabileceği bildirilmektedir. Bununla birlikte, kendine özgü aromatik yapısı, hafif acımsı tadı ve koyu renk tonu, özellikle açık renkli ürünlerde duyusal kabulü sınırlayabilecek unsurlar arasında yer almaktadır. Bu nedenle, çörek otu küspesinin gıda formülasyonlarında kullanımında uygun oranların ve işleme stratejilerinin belirlenmesi önem taşımaktadır. Bu çalışma kapsamında, çörek otu küspesinin model gıdalardaki kullanım potansiyelini ortaya koymak amacıyla yoğurt üzerine eklenen fonksiyonel un, yulaf–çörek otu bar ve kraker olmak üzere üç farklı model ürün geliştirilmiştir. Yapılan duyusal değerlendirmeler, küspenin kullanım oranına bağlı olarak ürünlerin aroma, renk ve genel beğenilirlik özelliklerinde değişimler oluşturduğunu ve uygun formülasyonlarla kabul edilebilir duyusal özelliklerin sağlanabildiğini göstermektedir. Sonuç olarak, soğuk pres çörek otu küspesi, uygun formülasyon stratejileri ile yalnızca bir yan ürün olmaktan çıkarak besin değeri yüksek ve fonksiyonel özellikler sunan alternatif bir bileşen olarak değerlendirilebilir. Bu çalışma, çörek otu küspesinin sürdürülebilir gıda sistemleri kapsamında kullanımına yönelik uygulamalı bir yaklaşım sunmaktadır.

Anahtar Kelimeler: Çörek Otu Küspesi, Besin değeri, Bitkisel protein, Diyet lif, Fonksiyonel Gıda Uygulamaları.

1. Giriş

Soğuk pres yağ üretimi son yıllarda tüketici tercihlerindeki doğallık eğilimiyle birlikte önemli ölçüde büyümüş, bu süreçte yağ ekstraksiyonu sonrası elde edilen küspe miktarı da artış göstermiştir. Çörek otu (*Nigella sativa* L.), *Ranunculaceae* familyasına ait, Orta Doğu, Güney Asya ve Kuzey Afrika'da yüzyıllardır hem baharat hem de geleneksel tıbbi bitki olarak kullanılan yıllık otsu bir bitkidir (Ahmad et al., 2013; Zaky et al., 2021). Tohumların biyoaktif bileşen açısından zengin yapısı, soğuk pres yağ endüstrisini cazip kılmış ancak aynı zamanda büyük miktarlarda besin açısından değerli küspe üretilmesine yol açmıştır (Łopusiewicz et al., 2022).

Çörek otu tohumları yaklaşık %22-40 sabit yağ, %18-23 protein, %8 diyet lifi ve %25-40 karbonhidrat içermektedir (Bashir et al., 2020; Zaky et al., 2021). Soğuk pres işlemi sırasında tohumun %15-25'i oranında artık yağ küspede kalırken protein, lif, mineral ve timokinon, fenolikler ve tokoferoller gibi biyoaktif bileşenler konsantre hale gelmektedir (Hallouch et al., 2024; Rabiej-Kozioł and Szydłowska-Czerniak, 2024; Çavdaroğlu et al., 2025). Bu bileşim profili, çörek otu küspesini fonksiyonel gıda bileşeni olarak son derece cazip kılmaktadır (Yabacı Karaoğlan, 2025).

Literatürde çörek otu küspe ununun ekmek (Yüksel et al., 2023), makarna (Krawęcka et al., 2022), glutensiz ürünler (Różyło et al., 2021) ve kurabiye (Batool et al., 2024) gibi fırın ürünlerinde kullanımı incelenmiş; protein, lif ve antioksidan kapasitesi üzerindeki olumlu etkileri raporlanmıştır (Yüksel et al., 2023). Łopusiewicz et al. (2022), çörek otu küspesinin fermente bitkisel kefir benzeri içecek üretimine de uygun olduğunu göstermiştir. Bununla birlikte, küspenin doğrudan insan beslenmesine yönelik pratik formülasyonlar kapsamında, yoğurt gibi süt ürünleriyle kombinasyonu, bar ve kraker gibi fırınlanmış atıştırmalıklardaki kullanımı ve bu uygulamalara ilişkin gerçek tüketici kabul verileri oldukça sınırlı kalmaktadır.

Bu çalışmanın amacı, soğuk pres çörek otu küspesinin (1) yoğurt üzeri fonksiyonel un (topping), (2) yulaf-çörek otu atıştırmalık bar ve (3) tohum kraker olmak üzere üç farklı model gıdadaki kullanım potansiyelini duyusal analiz yöntemiyle değerlendirmek ve ürün kategorisine özgü optimum küspe konsantrasyonlarını belirlemektir. Elde edilen bulgular, çörek otu küspesinin döngüsel ekonomi çerçevesinde sürdürülebilir gıda sistemlerine entegrasyonuna katkı sağlamayı hedeflemektedir.

2. Materyal ve Yöntem

2.1. Ham Maddeler

Çalışmada hammadde olarak Burdur ili Bucak ilçesinden temin edilen, soğuk sıkım yöntemiyle yağı alınmış çörek otu (*Nigella sativa* L.) küspesi kullanılmıştır. Pelet hâlindeki küspe, laboratuvar tipi bıçaklı değirmende öğütülmüş ve 500 µm altı partikül boyutuna elenerek homojenizasyon sağlanmıştır. Öğütülen un, mikrobiyolojik güvenlik amacıyla 125°C'de 10 dakika ön ısıl işleme tabi tutulmuştur.

Diğer ham maddeler olarak yulaf ezmesi, domates salçası (en az %32 kuru madde), biber salçası (en az %28 kuru madde), soğuk sıkım extra virgin zeytinyağı, iyotlu sofra tuzu, kekik, kabuksuz ayçekirdeği, kabak çekirdeği, karnıyarık otu tozu, keten tohumu ve tam yağlı sade yoğurt kullanılmıştır. Tüm bileşenler yerel marketlerden standart ticari ürünler olarak temin edilmiştir.

2.2. Atıştırmalık Bar Üretimi

Atıştırmalık bar üretiminde öncelikle çörek otu küspesi, yulaf ezmesi, tuz ve kekik homojen olacak şekilde karıştırılmıştır. Ayrı bir kapta domates ve biber salçası zeytinyağı ile emülsiyon hâline getirilmiştir. Kuru ve yaş karışımlar birleştirildikten sonra 25 mL su ilavesiyle homojen hamur elde edilmiştir. Her formülasyondan 4 adet, yaklaşık 4 cm × 8 cm × 1,5 cm boyutlarında şekillendirilmiş ve iki aşamalı pişirme uygulanmıştır: ilk aşamada 150°C'de 10 dakika, ardından 10. dakikada ters yüz edilerek 120°C'de 10 dakika daha pişirilmiştir. Ürünler fırın teli üzerinde oda sıcaklığına soğutulmuş ve 4±1°C'de muhafaza edilmiştir. Formülasyonlar Tablo 1'de sunulmaktadır; küspe oranları kuru madde bazında hesaplanmış olup fırınlama sırasında buharlaşan su miktarı dikkate alınmamıştır.

Tablo 1. Atıştırmalık Bar Formülasyonları

Bileşen	AB-K (Kontrol)	AB-F1	AB-F2	AB-F3	AB-F4
Çörek otu küspesi (g)	0,00	5,00	10,00	15,00	20,00
Yulaf ezmesi (g)	60,00	55,00	50,00	45,00	40,00
Domates salçası (g)	18,00	18,00	18,00	18,00	18,00
Biber salçası (g)	2,00	2,00	2,00	2,00	2,00
Zeytinyağı (g)	18,00	18,00	18,00	18,00	18,00
Tuz (g)	1,50	1,50	1,50	1,50	1,50
Kekik (g)	0,22	0,22	0,22	0,22	0,22
Su (mL)	25,00	25,00	25,00	25,00	25,00
Toplam-yaş ağırlık (g)	99,72	99,72	99,72	99,72	99,72

Çörek otu oranı* (KM)	**%0**	**%5**	**%10**	**%15**	**%20**

**Kuru madde bazında çörek otu küspesi oranı (fırınlama sonrası su buharlaşması dikkate alınarak hesaplanmıştır).*

2.3. Tohum Kraker Üretimi

Tohum kraker üretiminde kuru bileşenler önce homojen olarak karıştırılmıştır. Bağlayıcılık sağlamak amacıyla keten tohumu, 80-85°C'deki sıcak su ile muamele edilerek oda sıcaklığında 20 dakika bekletilmiş ve jelleşmesi sağlanmıştır. Jelleşen keten tohumu ve zeytinyağı kuru karışıma yavaşça eklenerek homojen bir kıvam elde edilmiştir. Hazırlanan karışım 10 cm × 21 cm ebadında ve 1 cm kalınlığında tepsiye yayılmış; çatal yardımıyla yüzeye delikler açılmış ve 8 eşit parçaya bölünmüştür. Pişirme önceden ısıtılmış fırında 150°C'de toplam 20 dakika süreyle gerçekleştirilmiş olup 10. dakikada ürünler ters yüz edilerek homojen pişirme sağlanmıştır. Formülasyonlar Tablo 2'de sunulmaktadır.

Tablo 2. Tohum Kraker Formülasyonları

Bileşen	TK-K (Kontrol)	TK-F1	TK-F2	TK-F3	TK-F4
Çörek otu küspesi (g)	0,00	5,00	10,00	15,00	20,00
Ayçekirdeği (g)	40,00	35,00	30,00	25,00	20,00
Kabak çekirdeği (g)	25,00	25,00	25,00	25,00	25,00
Karnıyarık otu tozu (g)	3,00	3,00	3,00	3,00	3,00
Kekik (g)	0,22	0,22	0,22	0,22	0,22
Zeytinyağı (g)	8,00	8,00	8,00	8,00	8,00
Tuz (g)	2,00	2,00	2,00	2,00	2,00

Keten tohumu (g)	5,00	5,00	5,00	5,00	5,00
Su-sıcak (mL)	50,00	50,00	50,00	50,00	50,00
Toplam-yaş ağırlık (g)	83,22	83,22	83,22	83,22	83,22
Çörek otu oranı* (KM)	**%0**	**%6**	**%12**	**%18**	**%24**

**Kuru madde bazında çörek otu küspesi oranı (fırınlama sonrası su buharlaşması dikkate alınarak hesaplanmıştır).*

2.4. Yoğurt Üzeri Fonksiyonel Toz Uygulaması

Çörek otu küspesinin süt ürünleriyle kombinasyon potansiyelini değerlendirmek amacıyla yoğurt üzeri fonksiyonel toz uygulaması tercih edilmiştir. Bu yaklaşım, küspenin pratik kullanım olanaklarını ve tüketici kabulünü doğrudan test etmeyi hedeflemiştir. Mikrobiyolojik güvenlik için 125°C'de 10 dakika pastörize edilen ve <500 µm partikül boyutuna sahip çörek otu unu, şeffaf mika tadım kaplarında hazırlanan 2 tatlı kaşığı sade yoğurt (tam yağlı) üzerine 1 çay kaşığı (~2-3 g) düzeyinde eklenerek tüketiciler tarafından değerlendirilmiştir. Tek konsantrasyonun test edilmesi, bu ürünün niteliği gereği, diğer ürünlerin aksine çok basamaklı ikame yerine pratik tek porsiyonluk uygulamaya daha uygun olmasından kaynaklanmaktadır.

2.5. Duyusal Analiz

Duyusal değerlendirme, Adana Alparslan Türkeş Üniversitesi Gıda Mühendisliği Bölümünde standardize edilmiş bireysel test alanlarında, kontrollü koşullarda (20-22°C, normal aydınlatma, sessiz ortam) gerçekleştirilmiştir. Çalışmaya üniversite personeli ve öğrencilerinden oluşmuş toplam 16 panelist (kadın/erkek: %78/%22; yaş aralığı: 23-58 yıl) davet edilmiş, katılım durumuna bağlı olarak atıştırmalık bar değerlendirmesinde n=16, tohum kraker ve yoğurt topping değerlendirmelerinde n=15 panelist yer almıştır.

Değerlendirmeler 9 noktalı hedonik skala (1 = hiç beğenmedim, 9 = çok beğendim) kullanılarak görünüş, koku, tat, lezzet, genel beğeni ve tercih etme kriterleri üzerinden yapılmıştır (Aigster et al., 2011; Stone et al., 2020). Panelistlere test öncesi gerekli bilgilendirme yapılmış ve onamları alınmıştır. Örnekler rastgele üç haneli kodlarla sunulmuş, tadımlar arasında su ve sade kraker ile ağız temizliği sağlanmıştır.

3. Bulgular ve Tartışma

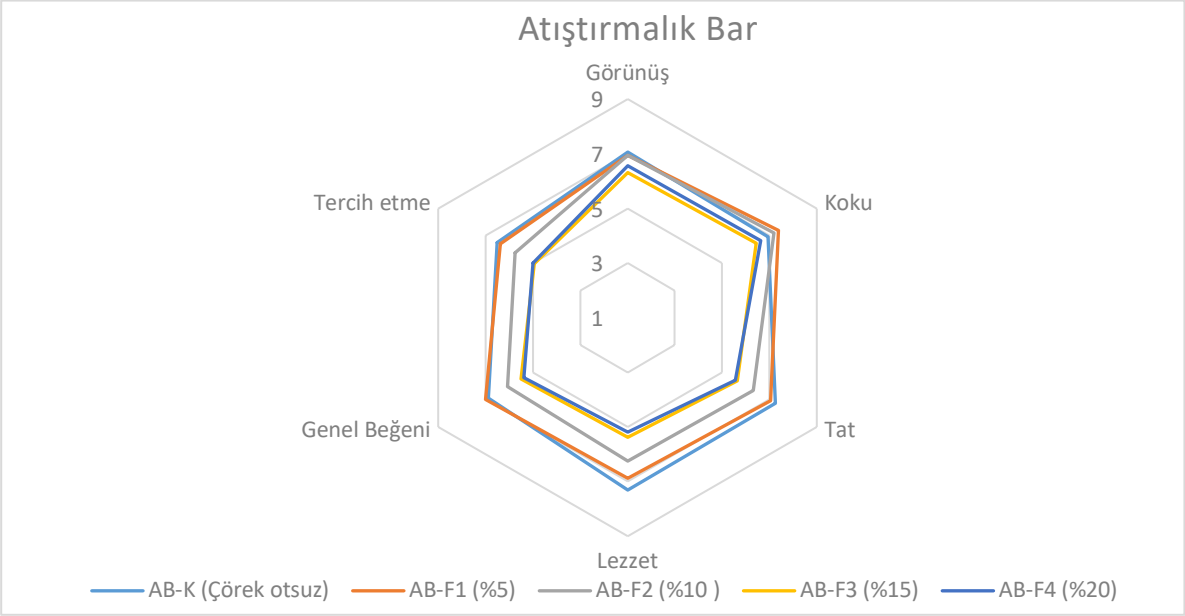
3.1. Atıştırmalık Bar Duyusal Analiz Sonuçları

Atıştırmalık bar formülasyonlarına ait duyusal analiz sonuçları Şekil 1'de verilmiştir. Çörek otu küspesi içermeyen kontrol grubu (AB-K), tat (7,25±1,48) ve lezzet (7,31±1,35) kriterlerinde en yüksek puanları almıştır. %5 küspe içeren AB-F1 formülasyonu ise koku açısından kontrol grubunu geride bırakmış (7,38±1,54 > 6,94±2,11) ve genel beğeni puanı kontrol grubuna yakın

seyretmiştir (7,00±1,51 ve 6,88±1,78). Bu bulgu, düşük konsantrasyonlarda çörek otu küspesinin barın aromasına kendine özgü olumlu bir katkıda bulunduğunu gösterebilir.

Küspe oranı arttıkça tüm kriterlerde düzenli bir düşüş gözlenmiştir. %15 ve %20 konsantrasyonlarında panelistler acılık şikayetlerini belirgin biçimde dile getirmiş, tercih etme puanı sırasıyla 4,94±2,02 ve 5,00±2,10 düzeyine gerilemiştir. Bu eğilim, literatürde benzer formülasyonlar için raporlanan bulgularla örtüşmektedir. Kamandloo et al. (2023) muffin çalışmalarında %3-6 aralığının duyusal kabul açısından optimum olduğunu bildirirken, Batool et al. (2024) kurabiye formülasyonlarında %10-15 oranında en yüksek duyusal puanlara ulaşılabileceğini belirtmiştir. Söz konusu sonuçlar, çörek otu küspesi unu kullanımının atıştırmalık bar ürünleri için %5-10 aralığının ticari potansiyel taşıdığına işaret etmektedir.

Şekil 1. Atıştırmalık Bar Formülasyonlarına Ait Duyusal Analiz Sonuçları (9-Puanlı Hedonik Skala, n=16)



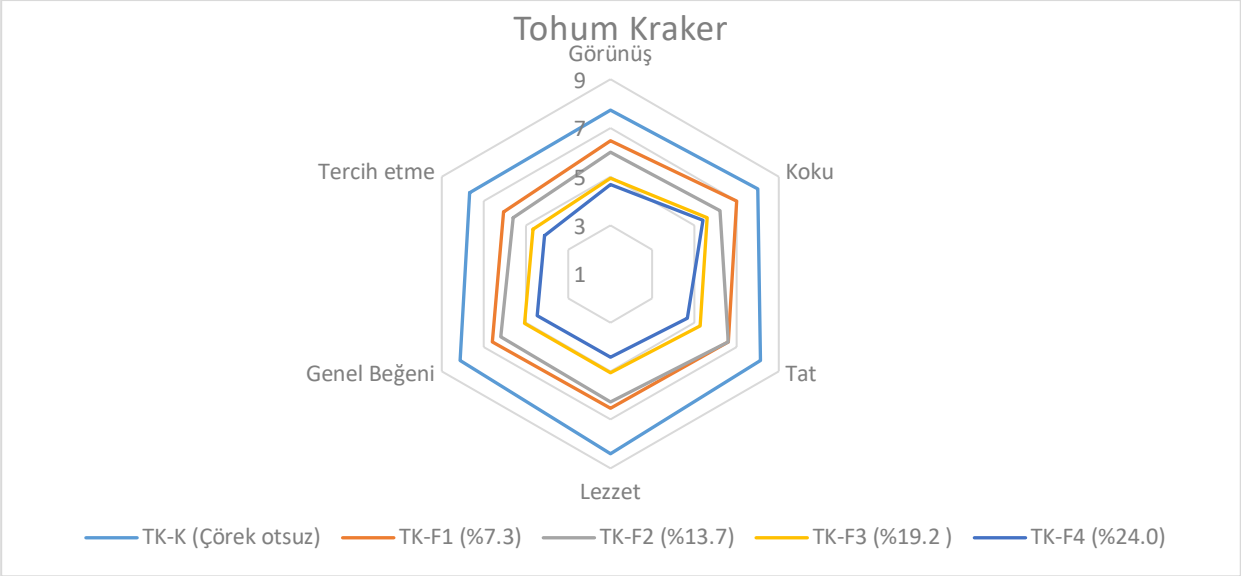
3.2. Tohum Kraker Duyusal Analiz Sonuçları

Tohum kraker formülasyonlarına ait duyusal sonuçlar Şekil 2'de yer almaktadır. Kontrol grubu (TK-K), tüm kriterler bakımından en yüksek puanları almış (7,47-8,07 aralığı) ve bu sonuç, temel tohum kraker formülasyonunun tüketici tarafından oldukça beğenildiğini ortaya koymuştur. Çörek otu küspesi ilavesiyle birlikte kabul edilebilirlik skorları sürekli ve anlamlı biçimde azalmış; %24 konsantrasyonundaki TK-F4'te tüm kriterlerde en düşük puanlara ulaşılmıştır (4,13-4,93 aralığı).

Bu düşüşün başlıca nedeni olarak yüksek konsantrasyonlarda artan acılık ve yoğun aroma etkileri öne çıkmaktadır; panelistler özellikle TK-F3 ve TK-F4 için tuzluluk ve acılık kombinasyonundan kaynaklanan olumsuz geri bildirimler iletmiştir. Benzer eğilimler Różyło et al. (2021) tarafından glutensiz ekmek formülasyonlarında %10 küspe eklendiğinde belgelenmiş; yüksek oranlarda sert aroma nedeniyle kabul edilebilirliğin düştüğü bildirilmiştir. Krawęcka et al. (2022) ise makarnadaki üst kullanım sınırını %20 olarak tanımlamıştır. Söz konusu bulgular, tohum kraker matrisinin çörek otu küspesinin baskın aromasına karşı sınırlı bir maskeleme kapasitesine sahip olduğunu düşündürmektedir; bununla birlikte %6

konsantrasyonunun (TK-F1) genel beğeni bakımından 6,93±1,67 ile hâlâ kabul edilebilir aralıkta kaldığı görülmüştür.

Şekil 2. Tohum Kraker Formülasyonlarına Ait Duyusal Analiz Sonuçları (9-Puanlı Hedonik Skala, n=15)

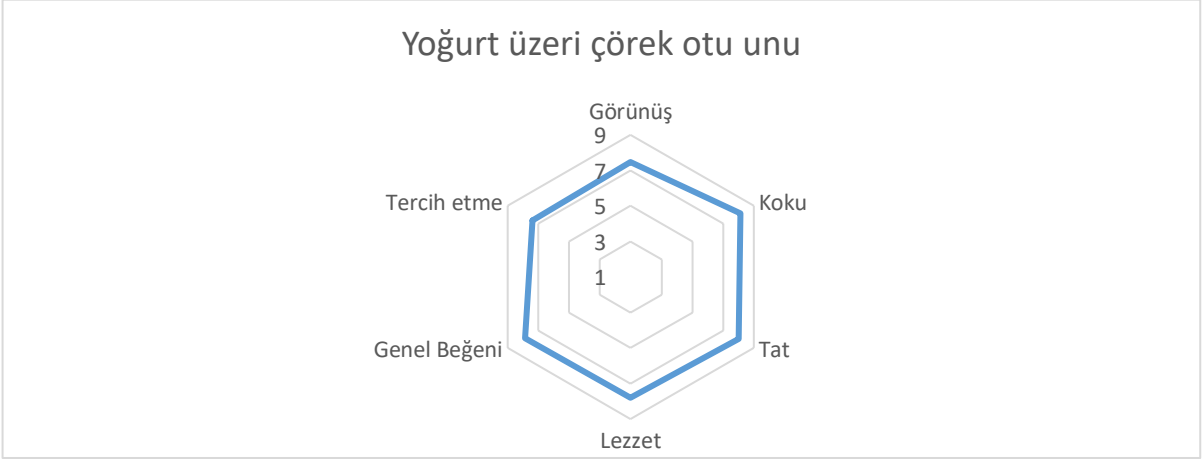


3.3. Yoğurt Üzeri Çörek Otu Unu (Topping) Duyusal Analiz Sonuçları

Yoğurt üzeri çörek otu unu uygulamasına ilişkin duyusal analiz sonuçları Şekil 3'te sunulmaktadır. Tek konsantrasyonda (~2-3 g) test edilen bu uygulama, üç ürün kategorisi arasında en yüksek duyusal kabul edilebilirliği sergilemiştir. Özellikle koku (7,56±1,59) ve görünüş (7,31±1,78) kriterleri belirgin biçimde ön plana çıkmış, panelistlerin %86,7'si (15 panelistten 13'ü) ürüne 7 ve üzeri puan vermiştir. Bazı panelistler 'yoğurt tadını baskılamıyor' ve 'günlük olarak tüketilebilir' şeklinde olumlu geri bildirimler iletmiştir.

Bu sonuçlar, çörek otu küspesinin süt ürünleriyle anlamlı bir tat uyumu sergilediğine işaret etmektedir. Yoğurdun kremalı ve hafif ekşimsi yapısının, küspenin kendine özgü acımsı notlarını dengeleyerek bu uyumu kolaylaştırdığı düşünülmektedir. Literatürde süt ürünleri ile yapılmış çörek otu formülasyonlarına rastlanmamış olsa da, Zaky et al. (2021) küspe proteinlerinin fonksiyonel özelliklerinin çeşitli gıda sistemlerinde olumlu tekstür ve duyusal katkı sağladığını vurgulamıştır. Mevcut çalışmanın yoğurt topping tadım bulguları, çörek otu küspesinin süt bazlı matrislere, puding ve benzeri kremalı ürünler dahil, başarıyla entegre edilebileceğine dair uygulamalı kanıt sunmaktadır.

Şekil 3. Yoğurt Üzeri Fonksiyonel Toz Duyusal Analiz Sonuçları (9-Puanlı Hedonik Skala, n=15)



3.4. Ürün Kategorilerinin Karşılaştırmalı Değerlendirmesi

Üç model ürünün ortalama genel beğeni puanları karşılaştırıldığında yoğurt topping uygulamasının (7,19) diğer kategorilere belirgin biçimde üstün olduğu görülmektedir. Atıştırmalık bar formülasyonları arasında AB-F1'in (%5) 7,00 puanla optimum düzeyi temsil ettiği, tohum kraker formülasyonlarında ise yalnızca TK-K ve TK-F1'in belirlenen kabul eşiğinin (≥7,0) üzerinde kaldığı anlaşılmaktadır.

Renk koyulaşması ve acılık, yüksek konsantrasyonlarda tüm ürün kategorilerinde ortak bir sınırlayıcı faktör olarak öne çıkmıştır. Bu bulgular, literatürdeki verilerle örtüşmekte; ekmekte %6-10, glutensiz ekmekte %8 ve kurabiyelerde %15-20 dolaylarında gözlenen kritik eşik değerlere paralel bir örüntü sergilemektedir. Çörek otu küspesinin matris tipine göre farklı kabul düzeyleri göstermesi, küspede bulunan fenolik bileşikler ve timokinonun farklı gıda bileşenleriyle olan etkileşim dinamiklerinden kaynaklanabilir (Trigui et al., 2021). Yüksek yağ ve protein içeriğinin, belirli matrislerde acılık algısını azaltabileceği de göz ardı edilmemelidir (Kamandloo et al., 2023).

4. Sonuç ve Öneriler

Bu çalışma, soğuk pres çörek otu küspesinin yoğurt üzeri fonksiyonel un, yulaf–çörek otu atıştırmalık bar ve tohum kraker olmak üzere üç farklı model gıda kategorisinde fonksiyonel bir bileşen olarak kullanılabilirliğini duyusal analiz yöntemiyle ortaya koymaktadır. Yazarların bilgisi dahilinde, soğuk pres çörek otu küspesi bir süt ürünü matrisiyle (yoğurt) ilk kez bu çalışmada birleştirilmiş ve duyusal açıdan değerlendirilmiştir. Yoğurt topping uygulaması üç ürün kategorisi arasında en yüksek kabul edilebilirlik düzeyini sergilemiş; bu bulgu, çörek otu küspesinin süt ürünleriyle anlamlı bir tat uyumu gösterebileceğine işaret etmektedir. Söz konusu uyumun, puding ve benzeri kremalı süt ürünlerine de aktarılabileceği ve bu tür ürünlerin besinsel profilini zenginleştirme potansiyeli taşıdığı değerlendirilmektedir.

Yulaf–çörek otu atıştırmalık barda %5-10, tohum krakerde ise %6 düzeyindeki küspe içerme oranlarının hem kabul edilebilir duyusal profil hem de artırılmış besinsel değer sunduğu ve bu aralıkların ticari açıdan uygulanabilir olduğu değerlendirilmektedir.

Gelecek çalışmalarda, çörek otu küspesinin fermente süt ürünleri başta olmak üzere farklı gıda matrislerindeki kullanım olanaklarının genişletilmesi öncelikli araştırma konuları arasında yer alabilir. Buna ek olarak, acılık maskeleme tekniklerinin (mikrokapsülleme, enzimatik muamele, yağ alma) duyusal profil üzerine etkileri incelenebilir. Tohum kraker formülasyonlarında panelistlerce dile getirilen tuzluluk şikâyetleri göz önünde bulundurulduğunda, tuz oranının azaltılmasının genel beğeniyi olumlu yönde etkileyebileceği öngörülmektedir. Geniş kapsamlı tüketici panelleri ve duyusal haritalama yöntemleri (RATA, CATA) aracılığıyla formülasyon optimizasyonu gerçekleştirilebilir. Öte yandan, küspede bulunan fenolikler ve minerallerden kaynaklanan biyoerişilebilirlik ve fonksiyonel etkinlik boyutlarının derinlemesine araştırılması, bu bileşenin sağlık iddialarına dayalı ürünlerdeki konumlanmasını güçlendirecektir.

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THE ROLE OF BİOCHEMİSTRY İN ELUCİDATİNG HUMAN DİSEASE MECHANİSMS

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ABSTRACT

Biochemistry has played a central role in advancing knowledge of human health and disease, from early discoveries of metabolic pathways to modern molecular medicine. This review aims to present a broad account of how biochemical processes shape the onset, progression, and outcomes of human diseases across the lifespan. The work traces the historical development of biochemical knowledge, linking classical studies of enzymes, hormones, and metabolism with recent advances in molecular biology, genomics, and biotechnology. The objectives of this review are to: (i) outline key biochemical principles underlying normal physiological function; (ii) describe how disruptions in these processes lead to disease conditions such as metabolic disorders, cancer, cardiovascular diseases, and neurodegenerative disorders; (iii) highlight the role of biochemical markers in diagnosis and disease monitoring; and (iv) discuss the contribution of biochemistry to therapeutic development and disease prevention strategies. Findings from the literature show that many diseases arise from alterations in cellular metabolism, enzyme function, genetic expression, and signaling pathways. For instance, abnormal glucose metabolism is closely linked with diabetes mellitus, while changes in cell signaling and gene regulation are strongly associated with cancer development. In addition, oxidative stress, inflammation, and defects in protein structure and function are common features shared by many disease conditions. Biochemical tools such as enzyme assays, molecular diagnostics, and biomarker profiling have improved early detection and guided treatment decisions in clinical practice. In conclusion, biochemistry provides a unifying basis for understanding disease mechanisms, from molecular alterations to systemic dysfunction and eventual mortality. Continued progress in biochemical research is essential for improving diagnostic accuracy, developing targeted therapies, and promoting preventive healthcare. It is recommended that future studies place greater focus on integrating biochemical data with clinical and environmental factors to enhance patient outcomes. Furthermore, increased investment in biochemical research and education will support innovation in disease management and global health.

Keywords: Biochemistry, Human diseases, Metabolism, Molecular biology, Disease mechanisms, Biomarkers, Cancer biology

1. Introduction

Biochemistry forms the foundation of modern biomedical science by providing a molecular-level understanding of life processes. It connects chemistry with biology to explain how cells function, respond to internal and external changes, and maintain homeostasis. Over time, this field has become central to medicine, particularly in explaining the origin and progression of human diseases.

At its core, biochemistry focuses on biomolecules such as proteins, carbohydrates, lipids, and nucleic acids, as well as the reactions they undergo within living systems. These molecules regulate vital processes including energy production, cell signaling, gene expression, and metabolic control. When these processes are disrupted, normal physiological balance is lost, leading to disease states. For example, impaired glucose metabolism results in diabetes mellitus, while alterations in DNA structure and gene regulation are strongly linked to cancer development (Nelson & Cox, 2021).

Human diseases are rarely caused by a single factor; rather, they arise from a combination of genetic, environmental, and biochemical disturbances. Enzyme deficiencies, hormonal imbalance, oxidative stress, and abnormal protein folding are among the major biochemical factors associated with disease conditions. In recent years, advances in molecular biology and biotechnology have further expanded knowledge in this area, allowing scientists to identify disease-related genes, proteins, and metabolic pathways with greater precision (Berg, Tymoczko, Gatto & Stryer, 2019).

Biochemistry also plays a major role in clinical practice through laboratory diagnostics. Measurement of biochemical markers such as enzymes, metabolites, and electrolytes provides valuable information for disease detection, monitoring, and management. For instance, elevated levels of cardiac enzymes are used in diagnosing myocardial infarction, while liver function tests help in assessing hepatic disorders (Burtis & Bruns, 2015).

Beyond diagnosis, biochemistry has influenced the development of therapeutic strategies. Many modern drugs are designed to target specific biochemical pathways, including enzyme inhibitors, receptor blockers, and gene-based therapies. This approach has improved treatment outcomes in various conditions, especially cancer and metabolic disorders.

This review presents a detailed account of how biochemistry supports the understanding of human disease mechanisms, from early discoveries to modern applications. It highlights the relationship between molecular changes and disease progression, emphasizing the role of biochemical knowledge in improving healthcare outcomes.

2. Historical Development of Biochemistry in Medicine

The development of biochemistry as a scientific discipline has been closely linked with progress in medicine. Early attempts to understand the chemical nature of life began in the late eighteenth century with the work of Antoine Lavoisier, who demonstrated that respiration is a form of combustion involving oxygen. His findings provided one of the first connections between chemical reactions and physiological processes, laying the groundwork for later studies on metabolism.

In the nineteenth century, major advances were made through the contributions of Justus von Liebig, who emphasized the importance of chemistry in agriculture and animal physiology.

Liebig proposed that bodily functions, including nutrition and energy production, could be explained through chemical transformations. Around the same period, Louis Pasteur made groundbreaking discoveries in fermentation, demonstrating that living organisms such as yeast play a role in biochemical reactions. His work helped disprove the theory of spontaneous generation and established a link between microorganisms and disease.

The late nineteenth and early twentieth centuries marked the emergence of biochemistry as a distinct scientific field. Eduard Buchner showed that fermentation could occur outside living cells using cell extracts, leading to the discovery of enzymes as biological catalysts. This discovery was essential in understanding how biochemical reactions occur within the body. At the same time, Emil Fischer made significant contributions to the study of proteins and carbohydrates, including the lock-and-key model of enzyme action, which explained enzyme specificity.

The identification of metabolic pathways in the early twentieth century further advanced medical biochemistry. Scientists such as Hans Krebs described the citric acid cycle, a central pathway in cellular energy production. This discovery helped explain how nutrients are converted into usable energy and highlighted the biochemical basis of metabolic diseases. Similarly, research into vitamins and coenzymes revealed their importance in maintaining normal physiological functions and preventing deficiency diseases.

A major turning point in biochemistry came with the discovery of the structure of DNA by James Watson and Francis Crick in 1953. This breakthrough provided a molecular explanation for heredity and genetic disorders. It also paved the way for the field of molecular biology, which focuses on gene expression and regulation. Subsequent developments, including recombinant DNA technology and genome sequencing, have allowed scientists to identify genetic mutations responsible for various diseases.

In recent decades, technological advancements have greatly expanded the scope of biochemistry in medicine. Techniques such as polymerase chain reaction (PCR), proteomics, and metabolomics have enabled detailed study of biomolecules in health and disease. These tools have improved disease diagnosis, monitoring, and treatment, particularly in areas such as cancer, infectious diseases, and genetic disorders (Berg et al., 2019; Nelson & Cox, 2021).

Overall, the historical progression of biochemistry reflects a continuous effort to understand life at the molecular level. From early chemical observations to modern molecular techniques, each stage has contributed to current knowledge of disease mechanisms and has strengthened the role of biochemistry in medical science.

3. Biochemical Basis of Normal Human Physiology

Normal human physiology depends on well-coordinated biochemical processes that occur within cells and tissues. These processes involve the interaction of biomolecules, regulated enzyme activity, and controlled metabolic pathways that maintain internal balance. Understanding these biochemical foundations is essential for recognizing how disruptions lead to disease.

Biomolecules form the structural and functional basis of all living systems. Proteins serve as enzymes, transporters, and structural components, while carbohydrates provide energy and participate in cell recognition. Lipids are essential for membrane structure, energy storage, and signaling, whereas nucleic acids store and transmit genetic information. The proper synthesis,

breakdown, and regulation of these molecules are necessary for maintaining cellular integrity and function (Nelson & Cox, 2021).

Enzymes are central to physiological processes because they speed up biochemical reactions under mild conditions. Each enzyme is specific to its substrate, ensuring that reactions occur in an orderly and regulated manner. Factors such as temperature, pH, substrate concentration, and the presence of inhibitors influence enzyme activity. Enzyme regulation occurs through mechanisms such as feedback inhibition and covalent modification, allowing cells to adjust metabolic rates based on their needs (Berg et al., 2019).

Metabolism consists of interconnected pathways that manage energy production and biosynthesis. These pathways are broadly divided into catabolism and anabolism. Catabolic processes break down complex molecules such as glucose, fatty acids, and amino acids to release energy, mainly in the form of adenosine triphosphate (ATP). One of the key pathways is Glycolysis, which converts glucose into pyruvate while generating ATP. This is followed by the Citric Acid Cycle and oxidative phosphorylation, which occur in the mitochondria and produce the majority of cellular energy.

Anabolic pathways, on the other hand, use energy to build complex molecules required for growth, repair, and maintenance. These include protein synthesis, lipid formation, and nucleic acid synthesis. The balance between catabolic and anabolic processes ensures that cells function efficiently under varying physiological conditions.

Cellular communication is another essential aspect of normal physiology. Signaling pathways allow cells to respond to hormones, neurotransmitters, and environmental changes. These signals are transmitted through receptors and intracellular messengers, leading to changes in gene expression and enzyme activity. Hormones such as insulin and glucagon regulate blood glucose levels by influencing metabolic pathways in tissues like the liver and muscle.

Homeostasis refers to the maintenance of a stable internal environment despite external changes. Biochemical systems play a major role in this process by regulating pH, temperature, electrolyte balance, and nutrient levels. Buffer systems, such as the bicarbonate buffer, help maintain blood pH within a narrow range. Similarly, the kidneys and lungs work together to regulate acid-base balance and remove metabolic waste products.

Disruptions in these biochemical processes can lead to physiological imbalance and disease. For instance, failure in enzyme function may result in metabolic disorders, while defects in signaling pathways can affect cell growth and communication. Therefore, a clear understanding of normal biochemical processes provides the foundation for identifying and managing disease conditions.

4. Biochemical Basis of Disease Mechanisms

Human diseases arise when normal biochemical processes are disrupted at the molecular or cellular level. These disruptions may result from genetic mutations, environmental factors, infections, or lifestyle-related influences. This section discusses major disease groups and the underlying biochemical changes that drive their onset and progression.

4.1 Metabolic Disorders

Metabolic disorders occur when the body is unable to properly process nutrients due to enzyme deficiencies, hormonal imbalance, or defects in metabolic pathways. One of the most common examples is diabetes mellitus, a condition characterized by impaired glucose regulation. In type 1 diabetes, there is destruction of pancreatic β-cells, leading to insufficient insulin production. In type 2 diabetes, cells become resistant to insulin, reducing glucose uptake and resulting in elevated blood glucose levels.

Biochemically, diabetes is associated with altered carbohydrate, lipid, and protein metabolism. Reduced insulin activity leads to increased gluconeogenesis, enhanced lipolysis, and the production of ketone bodies, which may cause ketoacidosis in severe cases. Persistent hyperglycemia also leads to non-enzymatic glycation of proteins, forming advanced glycation end products that damage tissues (American Diabetes Association, 2022).

Other metabolic disorders include inborn errors of metabolism such as phenylketonuria, where deficiency of phenylalanine hydroxylase results in accumulation of phenylalanine, leading to neurological damage if untreated. These conditions highlight the importance of enzymes in maintaining metabolic balance.

4.2 Cancer Biology

Cancer is a group of diseases characterized by uncontrolled cell growth and division. At the biochemical level, cancer involves alterations in gene expression, cell signaling pathways, and metabolic processes. Mutations in oncogenes and tumor suppressor genes disrupt normal cell cycle regulation, allowing cells to proliferate without control.

One important biochemical feature of cancer cells is altered energy metabolism. Many cancer cells rely heavily on Aerobic glycolysis, where glucose is converted to lactate even in the presence of oxygen. This metabolic shift supports rapid cell growth by providing intermediates for biosynthesis.

In addition, defects in apoptosis, the programmed cell death process, allow abnormal cells to survive longer than they should. Changes in signaling pathways such as those involving growth factors and kinases further promote tumor development. Oxidative stress and DNA damage also contribute to mutations that drive cancer progression (Hanahan & Weinberg, 2011).

4.3 Cardiovascular Diseases

Cardiovascular diseases are among the leading causes of death worldwide and are strongly linked to biochemical changes in lipid metabolism and vascular function. A key factor in these diseases is the accumulation of cholesterol and lipids in blood vessels, leading to atherosclerosis.

Low-density lipoprotein (LDL) cholesterol plays a major role in plaque formation. When LDL particles become oxidized, they are taken up by macrophages, forming foam cells that accumulate within arterial walls. This process narrows blood vessels and restricts blood flow, increasing the risk of heart attack and stroke.

Hypertension is another important cardiovascular condition, often associated with imbalances in electrolyte levels and hormonal regulation, particularly involving the renin-angiotensin system. Endothelial dysfunction, inflammation, and oxidative stress further contribute to vascular damage (Libby, 2021).

4.4 Neurodegenerative Diseases

Neurodegenerative diseases involve progressive loss of structure and function of neurons. These conditions are closely associated with abnormalities in protein structure, accumulation of toxic aggregates, and impaired cellular processes.

For example, Alzheimer's disease is characterized by the accumulation of beta-amyloid plaques and tau protein tangles in the brain. These abnormal protein deposits interfere with neuronal communication and lead to cell death. Similarly, Parkinson's disease involves the loss of dopamine-producing neurons and the accumulation of alpha-synuclein protein.

Oxidative stress and mitochondrial dysfunction are also major biochemical factors in neurodegeneration. The brain is particularly vulnerable to oxidative damage due to its high oxygen consumption and lipid content. Impaired antioxidant defenses further increase the risk of neuronal injury (Ross & Poirier, 2004).

4.5 Infectious Diseases

Infectious diseases are caused by pathogenic microorganisms such as bacteria, viruses, fungi, and parasites. These pathogens disrupt host biochemical processes to support their survival and replication.

Viruses, for example, depend on host cellular machinery for replication. Infections such as HIV/AIDS target immune cells, weakening the body's defense system. Bacterial infections may produce toxins that interfere with cellular metabolism or damage tissues.

The immune response to infection also involves complex biochemical processes, including the production of antibodies, activation of immune cells, and release of signaling molecules such as cytokines. While these responses help eliminate pathogens, excessive or uncontrolled reactions can lead to tissue damage and inflammation.

Summary of Section

Across all disease categories, a common theme is the disruption of normal biochemical processes. Whether through enzyme dysfunction, genetic mutation, altered metabolism, or external agents, these changes interfere with cellular function and lead to disease. Understanding these mechanisms provides a foundation for improved diagnosis, treatment, and prevention.

5. Biochemical Markers in Diagnosis and Prognosis

Biochemical markers play a central role in modern medicine by providing measurable indicators of normal biological processes, disease states, and responses to treatment. These markers, often detected in blood, urine, or other body fluids, assist clinicians in early diagnosis, monitoring disease progression, and predicting outcomes.

Enzymes are among the most widely used biochemical markers in clinical practice. Changes in enzyme levels often reflect tissue damage or organ dysfunction. For example, elevated levels of alanine aminotransferase (ALT) and aspartate aminotransferase (AST) are commonly associated with liver injury. Similarly, increased levels of creatine kinase (CK), particularly the CK-MB isoenzyme, are linked to cardiac muscle damage and are used in the diagnosis of myocardial infarction. These enzyme-based tests provide rapid and reliable information about organ health (Burtis & Bruns, 2015).

Cardiac biomarkers have advanced significantly with the introduction of proteins such as troponins. Cardiac troponin is highly specific for heart muscle injury and is now considered the gold standard for diagnosing acute coronary syndromes. Elevated troponin levels indicate damage to cardiac cells and help guide clinical decisions regarding treatment and patient management.

In addition to enzymes, metabolites and small molecules serve as important indicators of disease. Blood glucose levels are used in the diagnosis and monitoring of diabetes mellitus, while abnormal lipid profiles, including elevated cholesterol and triglycerides, are associated with cardiovascular diseases. Urea and creatinine levels are routinely measured to assess kidney function, as their accumulation in blood indicates impaired renal clearance.

Tumor markers are biochemical substances produced either by cancer cells or by the body in response to cancer. These markers are useful in detecting certain types of cancer, monitoring treatment response, and identifying recurrence. For instance, prostate-specific antigen (PSA) is used in the screening and management of prostate cancer, while alpha-fetoprotein (AFP) is associated with liver cancer. However, tumor markers are not always specific and are often used in combination with other diagnostic methods.

Advances in molecular biology have introduced new forms of biochemical markers based on genetic and protein analysis. Techniques such as polymerase chain reaction (PCR) and DNA sequencing allow detection of genetic mutations linked to inherited disorders and cancers. Proteomic and metabolomic approaches have further expanded the range of detectable biomarkers, enabling a more detailed understanding of disease processes at the molecular level (Henry et al., 2021).

Biochemical markers also play a role in prognosis by helping predict disease outcomes. For example, elevated levels of certain inflammatory markers may indicate disease severity, while specific genetic mutations can provide information about the likely course of cancer and response to therapy. This information supports personalized medicine, where treatment is tailored to the individual patient.

Despite their usefulness, biochemical markers have limitations. Factors such as biological variability, lack of specificity, and interference from other conditions can affect their accuracy. Therefore, results must be interpreted alongside clinical findings and other diagnostic tools.

In summary, biochemical markers are essential tools in modern healthcare. They provide valuable information for diagnosis, monitoring, and prognosis, and continue to evolve with advancements in biomedical research and technology.

6. Biochemistry in Drug Development and Therapy

Biochemistry plays a fundamental role in the discovery, design, and application of therapeutic agents used in the treatment of human diseases. By understanding the molecular basis of disease, scientists are able to develop drugs that target specific biochemical pathways, improving treatment outcomes and reducing unwanted effects.

One of the major approaches in drug development involves targeting enzymes that regulate metabolic and signaling pathways. Enzyme inhibitors are widely used as therapeutic agents. For example, drugs that inhibit key enzymes in cholesterol synthesis help reduce blood cholesterol levels and lower the risk of cardiovascular diseases. Similarly, inhibition of enzymes involved in microbial metabolism forms the basis of many antibacterial and antifungal therapies. These drugs work by interfering with essential biochemical processes in pathogens, thereby limiting their growth and survival (Rang et al., 2016).

Receptor-based therapies are another important area in biochemical pharmacology. Many drugs function by binding to specific cellular receptors, either activating or blocking them. This mechanism is commonly used in the treatment of conditions such as hypertension, asthma, and neurological disorders. By influencing receptor activity, these drugs help regulate physiological responses and restore balance in affected systems.

In recent years, advances in molecular biology have led to the development of targeted therapies, particularly in cancer treatment. Unlike traditional chemotherapy, which affects both healthy and diseased cells, targeted therapies are designed to act on specific molecules involved in tumor growth and progression. For instance, drugs that inhibit abnormal protein kinases can block signaling pathways that promote uncontrolled cell division. This approach has improved treatment precision and reduced toxicity in many cancer patients (Hanahan, 2022).

Biochemistry has also contributed to the development of biologic drugs, which are derived from living organisms. These include monoclonal antibodies, recombinant proteins, and vaccines. Monoclonal antibodies are designed to recognize and bind to specific antigens, such as those found on cancer cells or infectious agents. By targeting these molecules, they enhance the immune system’s ability to eliminate harmful cells.

Another important advancement is the application of gene-based therapies. Techniques that involve modifying or replacing defective genes have opened new possibilities for treating genetic disorders. Although still developing, these approaches aim to correct the underlying biochemical defects rather than simply managing symptoms.

Drug metabolism is another area where biochemistry plays a key role. Once administered, drugs undergo chemical modification in the body, primarily in the liver. These processes determine the drug’s activity, duration of action, and elimination. Enzymes such as those in the cytochrome P450 system are responsible for many of these transformations. Variations in these enzymes among individuals can influence drug response and may lead to differences in efficacy or adverse effects.

Despite significant progress, challenges remain in drug development. These include drug resistance, limited effectiveness in some patients, and potential side effects. Continuous research in biochemistry is therefore essential to improve drug design, identify new therapeutic targets, and enhance treatment strategies.

In summary, biochemistry provides the foundation for modern pharmacology and therapeutic innovation. By linking molecular knowledge with clinical practice, it supports the development of safer and more effective treatments for a wide range of diseases.

7. Biochemistry from Health to Death (System Failure and Mortality)

The transition from health to disease and ultimately to death involves progressive biochemical disturbances that affect cellular function, tissue integrity, and organ systems. Death is not an instantaneous event at the molecular level; rather, it is the result of cumulative failures in biochemical processes that sustain life.

At the cellular level, survival depends on continuous energy production, maintenance of membrane integrity, and proper regulation of ion balance. One of the earliest biochemical changes during severe illness or injury is a decline in ATP production, often due to impaired oxygen supply or mitochondrial dysfunction. Since ATP is required for essential processes such as active transport, protein synthesis, and cellular repair, its depletion leads to loss of cellular function and eventual cell death (Hall, 2021).

Hypoxia, a condition characterized by insufficient oxygen supply, plays a major role in many life-threatening conditions. Reduced oxygen availability limits oxidative phosphorylation in mitochondria, forcing cells to rely on anaerobic metabolism. This shift results in the accumulation of lactic acid, leading to decreased intracellular pH and metabolic acidosis. Prolonged acidosis disrupts enzyme activity and damages cellular structures.

Another important factor in the progression toward death is oxidative stress. An imbalance between the production of reactive oxygen species (ROS) and the body's antioxidant defenses leads to damage of lipids, proteins, and DNA. This damage contributes to the dysfunction of vital organs such as the brain, heart, liver, and kidneys. In severe cases, oxidative injury accelerates the breakdown of cellular systems and promotes irreversible damage.

Disturbances in calcium homeostasis also play a key role in cell injury and death. Under normal conditions, intracellular calcium levels are tightly regulated. However, during cellular stress or injury, calcium ions accumulate within the cytoplasm and mitochondria. This triggers the activation of enzymes that degrade cellular components, including phospholipids, proteins, and nucleic acids, further promoting cell damage.

As disease progresses, organ systems begin to fail. For example, in liver failure, there is impaired detoxification and accumulation of toxic metabolites such as ammonia. In kidney failure, the inability to excrete waste products leads to elevated levels of urea and creatinine in the blood. In heart failure, reduced cardiac output limits oxygen and nutrient delivery to tissues, worsening metabolic imbalance.

The process of cell death occurs mainly through two mechanisms: apoptosis and necrosis. Apoptosis is a regulated process that removes damaged or unwanted cells without causing inflammation. In contrast, necrosis results from severe injury and is associated with uncontrolled cell rupture and inflammation. Both processes are governed by biochemical pathways that determine cell fate under stress conditions.

In the final stages of life, widespread biochemical failure leads to systemic collapse. Loss of homeostatic control, severe metabolic disturbances, and multi-organ failure ultimately result

in death. Understanding these biochemical changes is important not only for clinical management but also for improving end-of-life care and preventing avoidable mortality.

8. Conclusion and Recommendations

Biochemistry remains a central pillar in understanding human life, health, and disease. From the molecular composition of cells to the regulation of complex physiological systems, biochemical processes govern the normal functioning of the human body. When these processes are altered, whether through genetic mutations, environmental factors, infections, or lifestyle influences, the result is the development and progression of disease.

This review has shown that many human diseases share common biochemical origins, including enzyme dysfunction, metabolic imbalance, oxidative damage, and disrupted cellular signaling. Conditions such as diabetes, cancer, cardiovascular diseases, and neurodegenerative disorders all arise from specific molecular changes that affect cellular stability and function. In addition, infectious agents interfere with host biochemical systems, further contributing to disease burden.

The role of biochemistry extends beyond understanding disease mechanisms to practical applications in diagnosis and treatment. Biochemical markers have improved the ability to detect diseases early, monitor progression, and guide clinical decisions. Similarly, advances in drug development have made it possible to design therapies that act on specific molecular targets, improving treatment precision and patient outcomes.

The progression from health to disease and eventually to death reflects a gradual breakdown of biochemical systems. Loss of energy production, accumulation of toxic metabolites, oxidative stress, and organ failure all represent stages in this process. Recognizing these changes provides valuable knowledge for medical intervention and prevention strategies.

Recommendations

1. Greater emphasis should be placed on integrating biochemical knowledge with clinical practice to improve disease management and patient care.

2. Investment in research focused on molecular mechanisms of disease should be increased to support the discovery of new diagnostic tools and therapeutic agents.

3. Development and use of advanced technologies such as genomics, proteomics, and metabolomics should be encouraged to enhance understanding of disease processes.

4. Public health strategies should incorporate biochemical knowledge, particularly in the prevention of metabolic and lifestyle-related diseases.

5. Continuous education and training in biochemistry should be promoted among healthcare professionals to ensure effective application of biochemical principles in medicine.

In conclusion, biochemistry provides a unifying foundation for understanding human disease from its origin at the molecular level to its final outcomes. Continued progress in this field will remain essential for advancing medical science, improving healthcare delivery, and reducing the global burden of disease.

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ASSESSMENT OF PARENTAL INVOLVEMENT IN CHILDREN'S EDUCATIONAL DEVELOPMENT IN JOS NORTH LOCAL GOVERNMENT AREA OF PLATEAU STATE, NIGERIA

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ABSTRACT

This study assessed parental involvement in children's educational development in Jos North Local Government Area of Plateau State, Nigeria. Four objectives and four research questions were formulated to guide the study. A survey research design was adopted, and the population comprised 334 households in the Anguwan Jarawa community, Jos North Local Government Area, Plateau State. A sample of 100 households was selected using a simple random sampling technique. A structured questionnaire titled ***Parental Involvement and Child Development Questionnaire (PICDQ)*** was used for data collection. The reliability of the instrument was established using the Cronbach Alpha method, yielding a reliability coefficient of **0.87**, indicating high internal consistency. The data collected were analysed using frequency counts, percentages, and mean scores. The findings revealed that parental involvement plays an important role in children's educational development in the study area. The study further showed that when parents are actively engaged in their children's academic, physical, social, and emotional lives, children tend to perform better and experience improved overall development. Based on the findings, it was recommended, among other things, that parents should be sensitised and empowered to actively support their children's education by participating in home-based learning activities, discussing school-related matters, and creating a conducive learning environment at home. It was also recommended that schools should provide platforms for parental engagement, such as parent–teacher conferences, learning workshops, and effective communication channels to promote regular collaboration between teachers and families.

Keywords: ***Parental Involvement, Educational Development, Cognitive Development, Social Development, Emotional Development***

Introductıon

Child development refers to the continuous process through which children grow and change physically, cognitively, emotionally, and socially from birth through adolescence. It involves the acquisition of knowledge, development of reasoning skills, emotional regulation, and the ability to interact effectively with others. This process is shaped by the interaction of genetic, environmental, and experiential factors and occurs in stages, where each stage builds on earlier experiences to produce a well-adjusted individual. Child development significantly influences learning outcomes, behaviour, and overall well-being across the lifespan. Child development is commonly categorized into four interrelated domains: cognitive, physical, social, and emotional development, all of which are essential for holistic growth (Rempel, 2022; Pomerantz et al., 2019). Cognitive development refers to children's ability to think, reason, solve problems, and understand their environment. It enables learners to process information and make informed decisions. Studies have shown that cognitive stimulation at home, particularly through parental support, enhances children's academic readiness and achievement (Fan & Chen, 2017; Jeynes, 2022).

Physical development involves growth in body structure, motor coordination, and general health. It includes both gross and fine motor skills such as walking, running, writing, and drawing. Research indicates that proper nutrition, parental supervision, and structured home environments contribute significantly to children's physical well-being and school readiness (Kimaro & Machumu, 2015; Epstein, 2021). Social development refers to how children learn to interact with others, build relationships, and understand societal norms. Through interactions with parents, peers, and teachers, children develop cooperation, empathy, and conflict resolution skills. Empirical evidence suggests that parental engagement improves children's social competence and peer relationships (Henderson & Mapp, 2022; Wilder, 2014).

Emotional development involves the ability of children to recognize, express, and manage their emotions, as well as understand the emotions of others. Children who receive consistent emotional support from parents are more likely to develop resilience, self-regulation, and confidence. Jeynes (2024) found that parental emotional engagement is associated with improved self-esteem and reduced behavioural challenges among children. Parental involvement refers to the active participation of parents or guardians in their children's educational and developmental processes. It includes home-based activities such as assisting with learning tasks and establishing routines, as well as school-based activities such as attending meetings and maintaining communication with teachers. Epstein's (2018) framework identifies six dimensions of parental involvement: parenting, communicating, volunteering, learning at home, decision-making, and collaborating with the community.

The assessment of parental involvement is important in understanding how different parental practices relate to children's developmental outcomes. This assessment focuses on key indicators such as home learning support, communication with teachers, participation in school activities, goal-setting practices, and modelling of behaviour. These indicators provide measurable ways of determining the level and quality of parental engagement in children's education and development (Epstein & Sheldon, 2018; Jeynes, 2022; Akindipe, 2025). Studies have shown that when parental involvement is effectively assessed and applied, it contributes positively to children's academic and developmental outcomes. For example, Jeynes (2022), in a meta-analysis, reported that parental involvement is significantly associated with improved academic performance, better behaviour, and enhanced emotional well-being among students.

Similarly, Akindipe (2025) found that structured parental engagement programmes improved students' academic achievement and self-efficacy within the Nigerian context.

Despite these findings, there remains a contextual gap in the assessment of parental involvement in relation to specific domains of child development in Jos North Local Government Area, Plateau State. Most existing studies focus mainly on academic performance, with limited attention to the assessment of cognitive, physical, social, and emotional development as separate outcomes. Therefore, this study seeks to address this gap by assessing parental involvement in relation to the holistic development of children in the study area.

Aım And Objectıves

The study aimed to assess parental involvement in the holistic development (cognitive, physical, social, and emotional) of children in Jos North Local Government Area, Plateau State. Specifically, the objectives of the study are to:

1. examine how parental involvement is expressed in the cognitive development of children in Jos North Local Government Area, Plateau State.
2. assess the role of parents in supporting the physical development of children in Jos North Local Government Area, Plateau State.
3. determine the ways in which parental involvement contributes to the social development of children in Jos North Local Government Area, Plateau State.
4. evaluate how parental involvement influences the emotional development of children in Jos North Local Government Area, Plateau State.

Research Questıons

1. **How is parental involvement expressed in the cognitive development of children in Jos North Local Government Area, Plateau State?**
2. **What role do parents play in supporting the physical development of children in Jos North Local Government Area, Plateau State?**
3. **In what ways does parental involvement contribute to the social development of children in Jos North Local Government Area, Plateau State?**
4. How does parental involvement influence the emotional development of children in Jos North Local Government Area, Plateau State?

Lıterature Revıew

Concept of Parental Involvement in Education

Parental involvement in education refers to the active participation of parents in their children's learning processes both at home and in school. It includes activities such as assisting with homework, attending school meetings, monitoring academic progress, and creating a supportive learning environment. Scholars conceptualize parental involvement as a multidimensional construct comprising home-based involvement, school-based involvement, and academic socialization. According to Joyce Epstein (2011), parental involvement can be categorized into six major types: parenting, communication, volunteering, learning at home, decision-making, and collaboration with the community. This framework emphasizes that effective parental engagement extends beyond homework assistance to include active participation in school governance and community partnerships. Empirical evidence, particularly within the Nigerian context, indicates that parental involvement significantly

contributes to students' academic success and overall development. Studies have shown that parents who actively monitor their children's academic activities and participate in school-related functions positively influence students' motivation, discipline, and academic achievement (Okeke, 2014; Eze, 2019; Hill & Tyson, 2009). Beyond academic outcomes, such involvement also supports children's social, emotional, and behavioral development (Jeynes, 2016; Fan & Chen, 2001).

Children's Educational Development

Children's educational development involves the acquisition of knowledge, skills, values, and competencies necessary for academic success and lifelong learning. It encompasses cognitive, social, emotional, and physical growth, all of which enable children to function effectively within school and society. The theoretical foundations of children's educational development are rooted in the works of Jean Piaget (1952) and Lev Vygotsky (1978). Piaget emphasized stages of cognitive development, highlighting how children actively construct knowledge, while Vygotsky stressed the importance of social interaction and guided learning in the development process. Contemporary research further emphasizes that children's development is strongly shaped by environmental factors, particularly parental support. A conducive home environment, parental encouragement, and access to learning resources significantly enhance children's academic performance, critical thinking abilities, and overall intellectual growth (Bornstein, 2022; Prime, Wade, & Browne, 2023). Similarly, studies have shown that supportive home learning environments and active parental engagement are associated with improved academic outcomes and cognitive development in children (Weisberg, Hirsh-Pasek, & Golinkoff, 2021; Moroni et al., 2022). Thus, parental involvement serves as a foundational factor influencing children's holistic educational development

Parental Involvement and Cognitive Development

Cognitive development refers to the development of children's thinking, reasoning, and problem-solving abilities. It involves mental processes such as memory, attention, perception, and language development, which are essential for academic achievement. Parental involvement plays a crucial role in enhancing cognitive development. Parents support learning by engaging children in intellectually stimulating activities such as reading, storytelling, assisting with homework, and encouraging inquiry-based discussions. These activities help develop language skills, critical thinking, and problem-solving abilities.

Empirical studies have established a strong relationship between parental involvement and academic achievement. For instance, Idris-Iyekolo (2024) found a significant relationship between parental involvement and students' academic performance in Kwara State. Similarly, Fajoju, Aluede, and Ojugo (2015) reported that increased parental involvement leads to improved performance in core subjects such as English and Mathematics. In addition, Prime, Wade, and Browne (2023) highlight that positive parenting practices enhance children's cognitive outcomes, while Weisberg et al. (2021) emphasize the role of guided play and parent–child interaction in promoting reasoning skills. Furthermore, Moroni et al. (2022) note that the quality of parental involvement—particularly supportive and non-controlling engagement—predicts better academic performance and cognitive growth. These findings underscore that both the presence and quality of parental involvement are critical in shaping children's intellectual development.

Parental Involvement and Social Development

Social development involves the acquisition of interpersonal skills, social behaviors, and the ability to interact effectively with others. These include communication, cooperation, empathy, and conflict resolution, which are essential for effective functioning in school and society. Parents play a vital role in shaping children's social competencies through modeling, guidance, and reinforcement of appropriate behaviors. The social learning theory of Albert Bandura (1977) explains that children learn behaviors through observation and imitation, particularly from significant adults such as parents. Positive parental involvement fosters the development of cooperation, empathy, communication skills, and respect for others. Empirical evidence indicates that children with active parental support exhibit better social adjustment, improved peer relationships, and fewer behavioral problems. Studies by Rubin, Bukowski, and Bowker (2022) show that parental warmth and involvement significantly predict positive social outcomes, while Denham et al. (2020) found that supportive parenting enhances social competence and reduces behavioral difficulties. Furthermore, parental participation in school and community activities provides children with opportunities to develop social skills and adapt effectively to different social environments. Masten and Barnes (2021) also emphasize that strong family relationships contribute to children's resilience and social adaptability.

Parental Involvement and Emotional Development

Emotional development refers to children's ability to understand, express, and regulate their emotions. It is a critical component of overall development, influencing social relationships, behavior, and academic success. Parental involvement is central to emotional development. Parents influence this aspect by providing emotional support, encouragement, and a secure and nurturing environment. Children who receive consistent parental care and attention tend to develop higher self-esteem, emotional stability, and resilience. Denham (2018) explains that emotional competence develops through interactions with caregivers who model and guide emotional expression. Supporting this view, Morris et al. (2022) found that parent–child emotional interactions significantly influence children's emotional regulation and well-being, while Brackett et al. (2021) reported that emotionally supportive parenting enhances emotional intelligence and social functioning. Conversely, lack of parental involvement may result in emotional challenges such as anxiety, low self-confidence, and poor emotional regulation. Durlak et al. (2021) further emphasize that collaboration between parents and schools in social-emotional learning programs improves children's emotional outcomes and overall adjustment. This highlights the importance of consistent parental engagement in fostering emotional stability.

Parental Involvement and Physical Development

Physical development involves the growth of the body and the development of motor skills necessary for effective functioning. It includes gross motor skills, fine motor skills, and overall physical health, which are essential for children's participation in learning and daily activities. Parents contribute significantly to this aspect of development by ensuring proper nutrition, healthcare, and opportunities for physical activities. Active parental involvement in promoting healthy habits enhances children's overall well-being and supports their participation in school-related activities.

Bornstein (2022) and Black et al. (2021) highlight that responsive parenting and supportive home environments significantly influence children's physical growth and health outcomes.

Similarly, Shonkoff et al. (2021) emphasize that stable and supportive caregiving relationships are fundamental to healthy physical development in early childhood. However, socioeconomic challenges in some Nigerian communities may limit parents' ability to adequately support their children's physical development. Despite these constraints, parental awareness, commitment, and active engagement remain critical factors in promoting healthy growth and physical well-being in children.

Methodology

This study adopted a survey research design to assess parental involvement in children's educational development in Jos North Local Government Area of Plateau State, Nigeria. The survey design was considered appropriate because it allows the researcher to collect data from a sample of respondents and describe existing conditions without manipulating any variables. It is suitable for obtaining information on respondents' perceptions regarding parental involvement and children's developmental outcomes in cognitive, physical, social, and emotional domains. The study was carried out in Jos North Local Government Area of Plateau State, Nigeria. The area is an urban setting comprising diverse communities, including Anguwan Jarawa. It is characterized by varying socio-economic backgrounds, which makes it appropriate for examining parental involvement in children's educational development across different household settings.

The population of the study comprised 334 households in Anguwan Jarawa community, Jos North Local Government Area of Plateau State. These households were considered relevant because they include parents or guardians responsible for children whose developmental outcomes were the focus of the study. A sample of 100 households was selected from the population using a simple random sampling technique. This sampling method was adopted to ensure that each household had an equal chance of being selected, thereby reducing bias and enhancing the representativeness of the sample. The instrument for data collection was a structured questionnaire titled ***Parental Involvement and Child Development Questionnaire (PICDQ)***. The questionnaire was designed by the researcher and consisted of two sections. Section A elicited demographic information of respondents, while Section B contained 20 items relating to parental involvement and children's cognitive, physical, social, and emotional development. The questionnaire items were structured on a four-point Likert scale of Strongly Agree (4), Agree (3), Disagree (2), and Strongly Disagree (1).

The instrument was validated through face and content validity by experts in Educational Psychology, Adult Education and Research, Measurement and Evaluation units, all from Faculty of Education, University of Jos, Plateau State, Nigeria. The experts assessed the items for clarity, relevance, and adequacy in measuring the intended variables. Their suggestions and corrections were incorporated into the final draft of the instrument to improve its quality. The reliability of the instrument was established using the Cronbach Alpha method. The questionnaire was administered to respondents outside the study area, but same population, and the responses were analysed to determine internal consistency. A reliability coefficient of 0.70 and above was considered acceptable for the study (Ugodulunwa, 2020). Data were collected through the direct administration of the questionnaire to the selected respondents with the assistance of trained research assistants. This approach ensured a high response rate and allowed clarification of items where necessary. The completed questionnaires were retrieved immediately after completion. The data collected were analysed using descriptive statistics, including frequency counts, percentages, and mean scores. A criterion mean of 2.50 was used as the decision rule. Mean scores of 2.50 and above were interpreted as Agree, while mean

scores below 2.50 were interpreted as Disagree. The results were presented in tables and interpreted in line with the research questions of the study.

Results

Research Question One

How is parental involvement expressed in the cognitive development of children in Jos North Local Government Area, Plateau State?

Table 1: Analysis of Responses on Parental Involvement in the Cognitive Development of Children

S/N	Statements	SA	A	D	SD	Mean	Standard Deviation	Decision
1	Children understand things better when parents help with homework or school tasks.	30	34	20	16	2.78	1.04	Agree
2	Reading with children at home helps them learn better.	35	33	18	14	2.89	1.04	Agree
3	Helping children solve learning problems improves their thinking skills.	28	36	20	16	2.76	1.03	Agree
4	Providing books or learning toys helps children's brain development.	27	35	22	16	2.73	1.03	Agree
5	Talking with children about what they learn in school supports their understanding.	26	37	21	16	2.73	1.02	Agree
	Grand Mean					**2.78**		

Source: Field Survey, 2025

Table 1 presents respondents' views on how parental involvement is expressed in the cognitive development of children in Jos North LGA. Item 2 recorded the highest mean score (2.89), indicating that many respondents agree that reading with children at home enhances their learning ability. Items 1, 3, 4, and 5 had mean scores ranging from 2.73 to 2.78, showing consistent agreement that parental practices such as helping with homework, assisting in problem-solving, providing educational materials, and discussing schoolwork support children's cognitive development. The standard deviation values, ranging from 1.02 to 1.04, indicate a low dispersion of responses, suggesting similarity in respondents' views. All items recorded mean scores above the criterion mean of 2.50, indicating agreement that parental

involvement plays an important role in supporting children's cognitive development. These practices enhance children's understanding, thinking ability, and problem-solving skills.

Research Question Two

What role do parents play in supporting the physical development of children in Jos North Local Government Area, Plateau State?

Table 2: Analysis of Responses on Parental Involvement in the Physical Development of children

S/N	Statements	SA	A	D	SD	Mean Score	Standard Deviation	Decision
6	Healthy meals from parents support children's growth.	36	34	20	10	2.96	0.98	Agree
7	Children grow stronger when allowed to play and move around.	26	36	24	14	2.74	1.00	Agree
8	Teaching children how to keep their bodies clean supports physical growth.	30	32	22	16	2.76	1.05	Agree
9	Physical activities with parents help children stay active.	28	30	22	20	2.66	1.09	Agree
10	Limiting screen time supports children's physical well-being.	24	30	24	22	2.56	1.08	Agree
	Grand Mean					**2.70**		

Source: Field Survey, 2025

Table 2 presents respondents' views on the role of parents in supporting the physical development of children in Jos North LGA. Item 6 had the highest mean score (2.96), indicating strong agreement that providing healthy meals supports children's growth. Items 7 and 8, with mean scores of 2.74 and 2.76 respectively, show that allowing children to engage in play and teaching personal hygiene contribute positively to physical development. Items 9 and 10, with mean scores of 2.66 and 2.56, also indicate agreement that parental involvement through physical activities and regulation of screen time supports children's well-being. The standard deviation values (0.98–1.09) show moderate agreement among respondents. The findings suggest that active parental practices such as providing nutritious meals, encouraging physical activity, and teaching personal hygiene play a crucial role in the physical development of

children. The responses emphasise that consistent engagement by parents supports healthier growth and physical well-being in early childhood.

Research Question Three

In what ways does parental involvement contribute to the social development of children in Jos North Local Government Area, Plateau State?

Table 3: Analysis of Responses on Parental Involvement in the Social Development of Children

S/N	Statements	SA	A	D	SD	Mean Score	Standard Deviation	Decision
11	Teaching children polite greetings improves social skills.	30	33	23	14	2.80	1.03	Agree
12	Playing with other children helps develop friendship skills.	35	32	20	13	2.89	1.01	Agree
13	Teaching children to share and take turns supports good behaviour.	29	34	22	15	2.76	1.04	Agree
14	Good manners in public places improve children's social behaviour.	27	19	24	30	2.48	1.07	Disagree
15	Praising children for good behaviour encourages positive social habits.	26	30	24	20	2.61	1.08	Agree
	Grand Mean					**2.71**		

Source: Field Survey, 2025

Table 3 shows respondents' views on how parental involvement contributes to the social development of children in Jos North LGA. Item 12 recorded the highest mean score (2.89), indicating strong agreement that interaction with peers enhances social skills. Items 11 and 13, with mean scores of 2.80 and 2.76, show that teaching greetings, sharing, and turn-taking supports positive social behaviour. Item 15 (2.61) also indicates agreement that praise encourages good social habits. However, Item 14 (2.48) fell below the criterion mean, suggesting disagreement among respondents regarding the role of enforcing good manners in public places. The standard deviation values (1.01–1.08) indicate moderate consistency in responses. The findings suggest that parental guidance, modelling, and reinforcement of positive behaviours play a key role in nurturing children's social development.

Research Question Four

How does parental involvement influence the emotional development of children in Jos North Local Government Area, Plateau State?

Table 4: Analysis of Responses on the Influence of Parental Involvement on Emotional Development of Children in Jos North LGA

S/N	Statements	SA	A	D	SD	Mean Score	Standard Deviation	Decision
16	Listening to children helps them understand their feelings.	36	32	19	13	2.90	1.01	Agree
17	Comfort from parents supports children's emotional well-being.	34	33	18	15	2.90	1.03	Agree
18	Guiding children to express feelings in good ways supports emotional control.	33	32	21	14	2.84	1.02	Agree
19	Talking to children about fear and stress builds emotional strength.	30	11	28	31	2.45	1.05	Disagree
20	Showing love and care daily builds children's emotional confidence.	29	30	23	18	2.70	1.06	Agree
	Grand Mean					**2.76**		

Source: Field Survey, 2025

Table 4 reveals responses on how parental involvement supports emotional development in preschool children. Items 16 and 17 had the highest mean scores (2.90 each), reflecting strong agreement that listening to children and offering comfort are critical to emotional well-being. Item 18 also showed notable agreement (2.84), pointing to the role of emotional guidance. Items 19 and 20, with mean scores of 2.45 and 2.70, suggest that talking about emotions and showing affection also contribute positively to emotional strength and confidence, albeit with slightly less consensus. The standard deviation values (ranging from 1.01 to 1.06) indicate consistency in respondent views. The findings show that emotional support from parents through active listening, reassurance, guidance, and love plays a vital role in the emotional development of children.

Discussion

This study assessed parental involvement in children's educational development in Jos North Local Government Area, Plateau State, Nigeria. The findings revealed that parental involvement is strongly reflected in children's cognitive development. Specifically, children whose parents assist with homework, read with them, provide learning resources, and discuss school activities demonstrate stronger cognitive outcomes. The mean scores, all above the criterion mean, indicate that respondents generally agree that these parental practices support children's thinking, understanding, and problem-solving abilities. This finding is consistent with Adeyemi (2018) and Ogunleye (2019), who found that consistent parental support at home, such as providing books and engaging children in problem-solving activities, enhances cognitive performance. Similarly, Okafor (2020) noted that parents' educational background contributes to exposing children to intellectually stimulating experiences, thereby improving academic achievement. This also aligns with Jeynes (2022) and Fan and Chen (2017), who

emphasized that home-based parental engagement plays a key role in children's cognitive development.

The findings further showed that parental involvement is clearly evident in children's physical development. Parents contribute through practices such as providing nutritious meals, encouraging physical activities, teaching personal hygiene, and regulating screen time. The high mean score recorded for healthy feeding indicates strong agreement among respondents that nutrition is fundamental to children's growth. These findings agree with Adekunle and Oladimeji (2018), who highlighted that those children who receive proper nutrition and parental support in physical activities tend to have better health and physical coordination. Similarly, Okeke (2020) and Abdullahi and Umar (2019) affirmed that parental involvement in daily routines, including exercise and hygiene practices, enhances children's physical well-being and motor skill development. The findings also support Epstein (2021), who emphasized the importance of structured home environments in promoting children's overall development.

The findings also indicated that parental involvement is evident in children's social development. Respondents agreed that practices such as teaching polite greetings, encouraging sharing and cooperation, promoting peer interaction, and reinforcing positive behaviour contribute to improved social skills. Interaction with peers recorded the highest mean score, suggesting that social engagement is a key aspect of development supported by parents. This finding corroborates Akinwale (2020) and Eze and Obi (2019), who observed that parental modelling of respectful and cooperative behaviours enhances children's ability to build strong peer relationships and develop social competence. It is also in line with Henderson and Mapp (2022), who noted that active parental engagement strengthens children's interpersonal skills. However, the slight disagreement on enforcing good manners in public places suggests that some aspects of social behaviour may not be consistently emphasized across all households.

Furthermore, the findings showed that parental involvement is clearly demonstrated in children's emotional development. Parents support emotional growth by listening to their children, providing comfort, guiding emotional expression, and showing love and care. The high mean scores for listening and providing comfort indicate that emotional support is a major component of parental involvement. These findings support the work of Chukwu and Nwosu (2021), who reported that emotionally responsive parenting promotes resilience and emotional stability in children. Similarly, Okonkwo (2020) and Durojaiye (2022) found that secure attachment, emotional guidance, and consistent parental care enhance children's emotional competence and reduce anxiety. This is also consistent with Jeynes (2024) and Pomerantz et al. (2019), who emphasized that supportive parenting improves children's emotional regulation and overall psychological well-being. However, the disagreement regarding discussions of fear and stress suggests that some parents may not fully engage in deeper emotional communication with their children.

The findings of the study show that parental involvement is actively expressed across the cognitive, physical, social, and emotional domains of child development. The assessment indicates that parents in the study area play significant roles in supporting their children's holistic development through various home-based and school-related practices. These findings are consistent with existing literature, which highlights the importance of parental engagement in promoting balanced and effective child development.

Conclusion

Based on the findings of this study, it can be concluded that parental involvement is a critical factor in the educational development of children in Jos North Local Government Area, Plateau State. The assessment revealed that when parents are actively engaged in their children's lives academically, physically, socially, and emotionally, children tend to perform better across all

domains of development. Such involvement supports cognitive growth, promotes healthy physical habits, enhances social skills, and strengthens emotional well-being. The study further highlights the importance of early and sustained parental engagement as a foundational element for holistic child development. It was observed that consistent parental participation in children's learning and daily activities contributes significantly to positive developmental outcomes. Conversely, limited parental involvement may hinder children's developmental progress and expose them to behavioural and academic challenges. The findings showed the need to prioritize parental involvement as a key strategy in supporting children's development. Therefore, parents, educators, and policy-makers should place greater emphasis on strengthening family engagement practices to ensure balanced and effective development among children.

Recommendatıons

Based on the findings of the study, the following recommendations are made:

1. Parents should be sensitised and empowered to actively support their children's education by participating in home-based learning activities, discussing school matters, and creating a conducive learning environment at home.
2. Schools should provide platforms for parental engagement, including parent-teacher conferences, learning workshops, and communication channels that encourage regular collaboration between teachers and families.

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COMPARATİVE ANALYSİS OF MACHİNE LEARNİNG MODELS FOR COD PREDİCTİON İN WASTEWATER TREATMENT PLANTS

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ABSTRACT

Efficient operation and control of wastewater treatment plants (WWTPs) critically depend on accurate prediction of chemical oxygen demand (COD), which serves as a key indicator of organic pollutant levels in wastewater. Reliable COD prediction enables plant operators to maintain environmental compliance, optimize treatment processes and reduce operational costs. Traditional monitoring approaches, which rely on laboratory-based COD measurements are often time-consuming and lack real-time applicability, creating a need for advanced predictive tools that can leverage online operational data. In this study, we investigate the predictive performance of Random Forest (RF), a widely used ensemble machine learning (ML) algorithm, in comparison with other popular ML models such as Artificial Neural Networks (ANN). The models were trained and validated using a comprehensive dataset collected from a full-scale WWTP, including key real-time physicochemical parameters such as pH, temperature, dissolved oxygen (DO), and total suspended solids (TSS). These parameters were selected due to their established influence on COD fluctuations and treatment efficiency. Model performance was evaluated using multiple metrics to provide a comprehensive assessment of predictive accuracy and reliability. Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used to quantify prediction errors, while the coefficient of determination (R^2) assessed the models' ability to capture variability in observed COD concentrations. The results indicate that RF consistently achieves the highest prediction accuracy across both training and validation datasets. In conclusion, this study demonstrates the superiority of RF for real-time COD prediction in wastewater treatment applications. The integration of RF-based predictive models into plant control systems represents a promising approach for enhancing operational efficiency, reducing reliance on laboratory testing and enabling data-driven wastewater management strategies. Future work could explore hybrid models combining RF with advanced deep learning techniques or the incorporation of additional environmental and operational variables to further enhance prediction performance.

Keywords: Wastewater Treatment Machine Learning, ANN, Random Forest.

ATIKSU ARITMA TESİSLERİNDE KOİ TAHMİNİ İÇİN MAKİNE ÖĞRENMESİ MODELLERİNİN KARŞILAŞTIRMALI ANALİZİ

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ÖZET

Atıksu arıtma tesislerinin verimli işletimi ve kontrolü, atık sudaki organik kirletici seviyelerinin temel bir göstergesi olan kimyasal oksijen ihtiyacının (KOİ) doğru şekilde tahmin edilmesine bağlıdır. Güvenilir KOİ tahmini için tesis operatörlerinin çevresel mevzuata uyum sağlanması, arıtma süreçlerinin optimize edilmesi ve işletme maliyetlerinin azaltılması gerekmektedir. Geleneksel izleme yaklaşımları, laboratuvar tabanlı KOİ ölçümlerine dayanmakta olup genellikle zaman alır ve gerçek zamanlı uygulamalara uygun değildir. Bu yüzden işletme verilerinden yararlanabilen gelişmiş tahmin araçlarına ihtiyaç vardır. Bu çalışmada, yaygın olarak kullanılan makine öğrenmesi algoritması olan Rastgele Orman (RO) modelinin tahmin performansı, Yapay Sinir Ağları (YSA) gibi diğer popüler makine öğrenmesi modelleri ile karşılaştırmalı olarak incelenmiştir. Modeller, pH, sıcaklık, çözünmüş oksijen (ÇO) ve toplam askıda katı madde (AKM) gibi temel gerçek zamanlı atıksu parametreleri atıksu arıtma tesisinden elde edilen bir veri seti kullanılarak eğitilmiş ve doğrulanmıştır. Bu parametreler, KOİ ve arıtma verimliliği üzerindeki bilinen etkileri nedeniyle seçilmiştir. Model performansı, tahmin doğruluğu ve güvenilirliğini kapsamlı bir şekilde değerlendirmek amacıyla birden fazla metrik kullanılarak analiz edilmiştir. Kök Ortalama Kare Hatası (RMSE) ve Ortalama Mutlak Hata (MAE) tahmin hatalarını ölçmek için kullanılırken, belirleme katsayısı (R^2) modellerin gözlenen KOİ değişkenliğini değerlendirmek için kullanılmıştır. Elde edilen sonuçlar, RO modelinin hem eğitim hem de doğrulama veri setlerinde tutarlı bir şekilde en yüksek tahmin doğruluğunu sağladığını göstermektedir. Sonuç olarak, bu çalışma atık su arıtma uygulamalarında gerçek zamanlı KOİ tahmini için Rastgele Orman yönteminin üstünlüğünü ortaya koymaktadır. RO tabanlı tahmin modelleri tesis kontrol sistemlerine operasyonel verimliliğin artırılması, laboratuvar testlerine olan bağımlılığın azaltılması ve atıksu yönetimi stratejilerinin geliştirilmesi açısından bir yaklaşım sunmaktadır. Gelecek çalışmalarda, RO ile gelişmiş derin öğrenme tekniklerinin birleştirildiği hibrit modellerin geliştirilmesi veya ek çevresel ve operasyonel değişkenlerin modele dahil edilmesiyle tahmin performansının daha da artırılması araştırılabilir.

Anahtar Kelimeler: Atıksu Arıtma, Makine Öğrenmesi, YSA, Rastgele Orman Algoritması.

1.Giriş

Günümüzde, küresel iklim değişikliği, kentleşme ve sanayileşme gibi dinamiklerin etkisiyle su, öncelikli bir kaynak haline gelmiştir (Evsahibioğlu, 2010). Artan su talebi, doğal su kaynaklarının daha verimli kullanılmasını ve su arıtma ile atıksu yönetimi sistemlerinin etkinliğinin artırılmasını zorunlu kılmıştır (Gürcan ve Açıksöz, 2023). Su arıtma tesisleri, işletme koşullarındaki değişkenlikler nedeniyle sürekli olarak gelişmiş teknolojik yaklaşımlarla modernize edilmesi gereken kritik altyapı sistemleri arasında yer almaktadır (Kırtorun ve Karaer, 2018). Su arıtma prosesleri, geleneksel kontrol yöntemleri kullanarak yönetilmesi gittikçe zorlaşmaktadır (Akkurt ve Oğuz, 2019). Bunun sebebi ise mevsimsel değişiklikler, kimyasal dengesizlikler ve değişken yükler gibi etkilerle yüksek derecede karmaşıklığa sahiptir (Yıldız vd., 2013). Bu yüzden atıksu arıtma tesisleri dinamik ve karmaşık altyapı sistemleri olduğundan sürecin verimli yönetilmesi ve ekonomikliği ile hassas bir denge kurmak zorundadır (Akmırza vd., 2017). Bu bağlamda, su arıtma süreçlerinde hem verimliliği artırmak hem de süreçlerin karmaşıklığını azaltmak amacıyla yapay zeka (YZ) ve makine öğrenimi (MÖ) gibi ileri teknolojiler kullanılmaya başlanmıştır (Civelekoğlu, 2006). Bunun temel sebebi, bu araçların model tabanlı tahmin, anomalilerin erken tespiti, gerçek zamanlı kontrol, öngörülü bakım gibi birçok başarılı uygulama alanında etkili çözümler sunabilmesidir (Demircioğlu, 2024). YZ tabanlı sistemler, KOİ tahmininden kimyasal kullanımı en aza indirmeye kadar geniş bir uygulama imkânı sunmaktadır (Waqas vd., 2022). Son yıllarda su arıtma süreçlerinin geliştirilmesi kapsamında, veri analitiği, ileri düzey modelleme teknikleri ve otomatik kontrol sistemlerinin entegrasyonu sayesinde arıtma verimliliği artırılmıştır (Akmırza vd., 2017). Bu konuda destek vektör regresyonu (SVR), YSA ve RO gibi algoritmalar, su kalitesi parametrelerinin tahmini ve süreç optimizasyonu konularında belirgin olarak kullanılmaktadır (Biau, 2010).

Bu çalışma, benzer araştırmalara ek olarak YZ/MÖ modellerinin oluşturulması için gerekli veri altyapısını ve algoritma tasarımlarını ele almakta, aynı zamanda geleceğe yönelik araştırma önerilerini de içermektedir. Bu sayede, su arıtma tesislerinin dijital dönüşüm süreçlerine ve sürdürülebilir yönetim stratejilerine önemli vurgu yapması hedeflenmiştir.

2. Yapay Zeka Uygulamaları

Atıksu arıtma tesisleri, süreç dinamiklerindeki karmaşıklık ve değişkenlik gibi nedenlerle verimlilik optimizasyonuna ihtiyaç duyan kritik altyapı tesisleri arasında yer almaktadır (Akmırza vd., 2017). Geleneksel kontrol ve izleme yöntemleri, bu karmaşıklığı yeterince yönetememekte ve sistem performansını sınırlı düzeyde artırabilmektedir (Akkurt ve Oğuz, 2019). Su arıtma tesislerinde yapay zeka (YZ) ve makine öğrenmesi (MÖ) teknolojilerinin uygulamaları hızla yaygınlaşmaktadır. Özellikle YZ tabanlı sistemler kritik rol oynamaktadır. Son yıllarda yapay zeka (YZ) ve makine öğrenmesi (MÖ) tabanlı yöntemler, bu sınırlamaları aşmak ve su arıtım süreçlerini daha esnek, öngörülebilir ve verimli hale getirmek amacıyla önemli bir alternatif olarak ortaya çıkmıştır (Aghdam vd., 2023). YZ ve MÖ teknikleri, özellikle büyük veri analizi, süreç değişkenlerinin optimizasyonu, anomali tespiti ve ileri süreç kontrolü alanlarında etkili çözümler sunmaktadır (Demircioğlu, 2024). Süreç verilerinin gerçek zamanlı analizi ve model tabanlı kontrol sistemlerinin uygulanması sayesinde arıza tahmini yapılması ve su kalitesi parametrelerinin daha hassas bir şekilde izlenmesi mümkün olabilmektedir (Chen vd., 2023). Bu gelişmeler, su arıtma tesislerinin çevresel etkilerini azaltarak sürdürülebilirlik hedeflerine de katkı sağlamaktadır (Gürcan ve Açıksöz, 2023).

Atıksu arıtma tesislerinin etkin ve sürdürülebilir işletimi, hem çevresel düzenlemelere uyumun sağlanması hem de alıcı ortamların korunması açısından kritik bir öneme sahiptir. Bu tesislerde çıkış suyu kalitesinin sürekli izlenmesi ve kontrol altında tutulması, arıtma performansının değerlendirilmesinde temel bir gerekliliktir. Bu bağlamda, organik kirletici yükünün en önemli göstergelerinden biri olan KOİ, arıtma süreçlerinin verimliliğinin belirlenmesinde yaygın olarak kullanılan temel parametrelerden biridir. Atık su arıtma tesislerinde KOİ miktarının doğru tahmin edilmesi, su kalitesi yönetimi ve planlanmasında çok önemli bir rol oynamaktadır. Atık su yönetim ve planlamasında yararlanılan ana parametrelerden birisi olan KOİ ölçümü hazırlık ve analiz aşamalarını içerir. Geleneksel KOİ ölçüm yöntemleri laboratuvar temellidir ve zaman alıcı, maliyetli ve gerçek zamanlı kontrol açısından yetersizdir. Bu nedenle, son yıllarda veri temelli yaklaşımlar özellikle makine öğrenmesi algoritmaları, çevresel sistemlerin modellenmesinde yoğun şekilde kullanılmaya başlanmıştır. Atıksu arıtma tesislerinde KOİ tahmini, süreç kontrolü ve çevresel uyumluluk açısından kritik bir rol oynamasına rağmen, mevcut geleneksel ölçüm yöntemleri gerçek zamanlı izleme ve hızlı karar verme süreçleri için yeterli değildir. Laboratuvar tabanlı analizlerin zaman alıcı olması, operasyonel gecikmelere neden olmakta ve arıtma sürecinin dinamik yapısının anlık olarak kontrol edilmesini zorlaştırmaktadır. Bu durum, özellikle değişken yük koşullarına sahip modern arıtma tesislerinde önemli bir problem teşkil etmektedir. Yapılan bir çalışmada, Van ilindeki bir atık su arıtma tesisinden elde edilen veriler kullanılarak biyokimyasal oksijen ihtiyacı (BOİ) parametresini pH, sıcaklık, iletkenlik, çözünmüş oksijen, askıda katı madde, toplam azot ve toplam fosfor gibi ölçülebilir parametrelerle tahmin edilebilirliğini araştırmışlardır. Bu amaçla ileri beslemeli YSA ve çoklu doğrusal regresyon analizi (ÇRA) yöntemleri kullanılmış, YSA modeli %99,83 doğruluk ve %0,12 MAPE değeri ile daha üstün performans sergilemiştir (Sidal ve Altun, 2023). Bir diğer çalışmada, tez çalışmasında, Sakarya'daki bir atıksu arıtma tesisinde laboratuvar ortamında ölçümü uzun süren BOİ5 parametresinin çevrim içi olarak parametreler kullanılarak yapay zeka ve makine öğrenmesi teknikleriyle hızlı ve doğru bir şekilde tahmin edilmesi amaçlanmıştır. Çalışmada, BOİ5 tahmini için YSA ve doğrusal regresyon gibi yöntemleri içeren hibrit bir model geliştirilmiş ve bu modelin doğruluğunu artırmak için veri dengeleme adımları uygulanmıştır. Sonuçlar, %97,18 R^2 ve %6,07 MAPE değerine ulaşarak algoritmasının en başarılı model olduğunu ortaya koymuştur (Selvi, 2019). Literatürde yapılan güncel çalışmalarda, makine öğrenmesi tabanlı modellerin KOİ tahmininde yüksek doğruluk sağladığı gösterilmektedir. Yapılan bir çalışmada, RO yöntemi klasik regresyon modellerine göre daha düşük hata oranı ile KOİ tahmini gerçekleştirdiği rapor edilmiştir (Zhou vd., 2019) Benzer şekilde, 2023 yılında gerçekleştirilen bir başka çalışmada, yapay sinir ağlarının doğrusal olmayan proses değişkenlerini modellemede üstün performans gösterdiği ve özellikle gerçek zamanlı izleme sistemlerinde kullanılabilir olduğu belirtilmiştir (Djeldjli vd., 2023). Ayrıca, derin öğrenme ve hibrit modellerin kullanımı da giderek artmaktadır. 2023 yılına ait güncel çalışmalar, YSA tabanlı modellerin optimizasyon algoritmaları ile desteklendiğinde KOİ tahmin doğruluğunun önemli ölçüde arttığını ortaya koymuştur (Sidal ve Altun, 2023).

Bu çalışmada, YSA ve RO algoritmalarının performansı karşılaştırmalı olarak ele alınmaktadır. Amaç, bu iki güçlü makine öğrenmesi yaklaşımının KOİ tahminindeki doğruluk, genelleme kabiliyeti ve uygulanabilirlik açısından değerlendirilmesidir. Bu kapsamda, KOİ tahmini için YSA ve RO modellerinin aynı veri seti üzerinde kapsamlı ve karşılaştırmalı analizi yapılmıştır. Parametre değişkenleri arasındaki ilişkilerin hem YSA hem de RO yaklaşımlarıyla nasıl temsil edildiği analiz edilmiştir. RO modelinin değişken önem analizi ile birlikte YSA modelinin yüksek doğruluk performansı karşılaştırmalı olarak sunulmuştur. Bu yönleriyle çalışma, yalnızca KOİ tahminine yönelik bir modelleme çalışması olmasının yanı sıra atık su arıtma sistemlerinde uygulanabilir yapay zeka tabanlı karar destek sistemlerinin geliştirilmesine

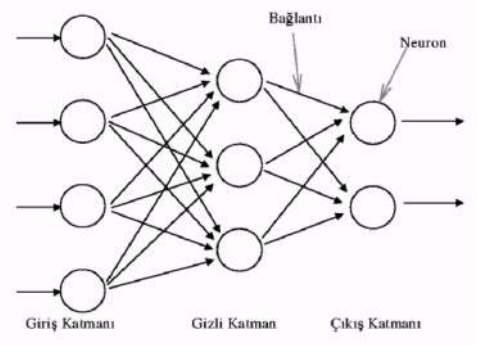
katkı sağlamaktadır. Model girişinde genellikle pH, sıcaklık, çözünmüş oksijen (DO) ve askıda katı madde (AKM) parametreler kullanılır. Bu parametreler ile KOİ arasındaki ilişki doğrusal olmadığından, RO gibi yöntemler oldukça uygundur. Model başarısını ölçmek için yaygın kullanılan metrikler şunlardır. R^2 (Determinasyon Katsayısı) RMSE (Kök Ortalama Kare Hata) MAE (Ortalama Mutlak Hata) değerleridir.

3. Yapay Sinir Ağları

YSA, insan beynindeki nöronların çalışma prensiplerinden esinlenerek geliştirilmiş, karmaşık ve doğrusal olmayan ilişkileri modelleme yeteneğine sahip güçlü makine öğrenmesi algoritmalarıdır. Özellikle çok değişkenli ve doğrusal olmayan sistemlerde, klasik istatistiksel yöntemlerin yetersiz kaldığı durumlarda yüksek performans göstermektedir. Bu özellikleri nedeniyle YSA, çevresel mühendislik uygulamalarında, özellikle atık su arıtma proseslerinin modellenmesi ve kalite parametrelerinin tahmin edilmesinde yaygın olarak kullanılmaktadır. Literatürde, YSA modellerinin su kalitesi tahmininde üstün performans sergilediği birçok çalışma bulunmaktadır. Gerçek zamanlı atık su izleme sistemlerinde YSA kullanımının KOİ tahmin doğruluğunu önemli ölçüde artırdığını ve doğrusal olmayan proses dinamiklerini başarıyla temsil ettiğini rapor etmiştir (Selvi, 2019). Benzer şekilde YSA modellerinin çok değişkenli çevresel veri setlerinde klasik regresyon yöntemlerine kıyasla daha düşük hata oranları sunduğunu göstermiştir. Ayrıca optimize edilmiş geri yayılım algoritmaları ile eğitilen YSA modellerinin, özellikle gürültülü ve eksik veri içeren sistemlerde daha kararlı sonuçlar ürettiğini vurgulamıştır (Djeldjli vd., 2023). Yapay Sinir Ağı modeli temel olarak üç ana katmandan oluşmaktadır. Giriş Katmanında bu çalışmada pH, sıcaklık, çözünmüş oksijen (DO), askıda katı madde (AKM) gibi operasyonel parametreler giriş değişkenleri olarak kullanılmıştır. Gizli Katmanlar, girdi ve çıktı arasındaki karmaşık doğrusal olmayan ilişkilerin öğrenildiği katmanlardır. Literatürde tek gizli katmanlı modellerin birçok mühendislik probleminde yeterli performans sağladığı, ancak daha karmaşık sistemlerde çok katmanlı yapıların daha başarılı olduğu belirtilmiştir. Çıkış Katmanında ise modelin tahmin ettiği hedef değişkeni üretir. Bu çalışmada çıkış değişkeni KOİ (mg/L) değeridir. Modelin matematiksel olarak temel yapısı aşağıdaki şekilde ifade edilir:

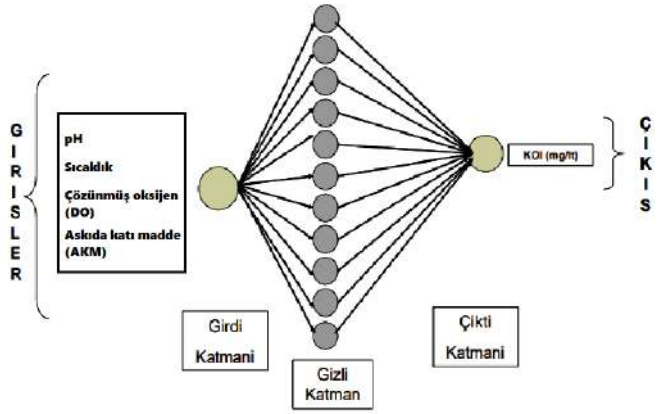
$$y = f(\sum_{i=1}^{n} w_i\, x_i + b) \quad (1)$$

Denklem 1 de x_i giriş değişkenlerini, w_i ağırlıkları, b bias terimini ve f aktivasyon fonksiyonunu temsil etmektedir.



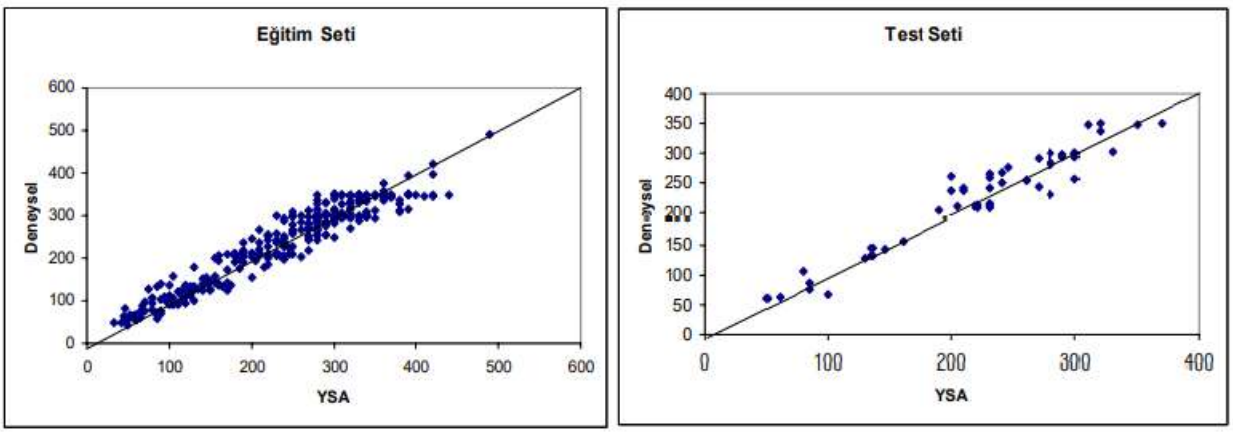
Şekil 1. Bir Yapay Sinir Ağı Modeli Gösterimi

YSA en önemli avantajları Şekil 1 de özetlenmiştir: Doğrusal olmayan ilişkileri öğrenme yeteneği ile YSA modelleri, atık su arıtma sistemleri gibi karmaşık ve doğrusal olmayan süreçleri etkili şekilde modelleyebilir. Yüksek tahmin doğruluğu içeren özellikle büyük veri setlerinde, Şekil 2 de YSA modellerinin KOİ gibi çevresel parametrelerin tahmininde yüksek doğruluk sağladığı birçok çalışmada gösterilmiştir. Uygun şekilde eğitildiğinde YSA modelleri, daha önce görülmeyen veri setleri üzerinde de başarılı tahminler yapabilmektedir.



Şekil 2. Önerilen YSA modeli

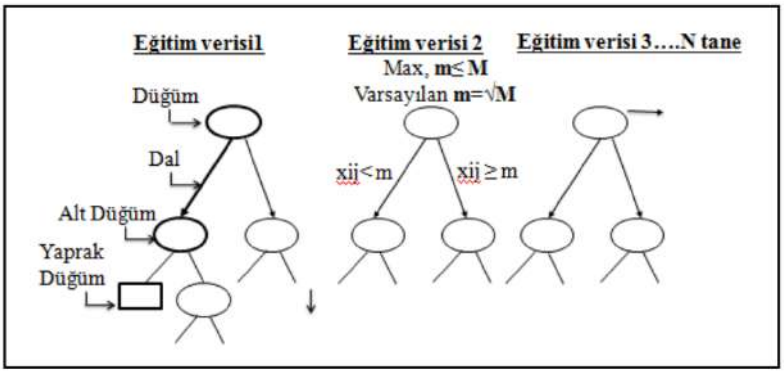
Bununla birlikte YSA modellerinin bazı sınırlamaları da bulunmaktadır. Özellikle küçük veri setlerinde model, eğitim verisine aşırı uyum sağlayarak genelleme performansını düşürebilir. YSA modelleri genellikle kara kutu olarak kabul edilir ve karar mekanizması kolayca yorumlanamaz. Bu durum, özellikle mühendislik uygulamalarında önemli bir dezavantajdır. Şekil 3 de YSA istenen sonuçların eğitim ve test seti verilmektedir. Burada verinin %80 i eğitim seti olarak, %20 si test seti olarak kullanılmıştır. Büyük veri setlerinde ise model eğitimi uzun sürebilir ve yüksek işlem gücü gerektirebilir. Sonuç olarak, YSA modelleri atık su arıtma tesislerinde KOİ tahmini gibi karmaşık çevresel problemlerin çözümünde yüksek potansiyele sahip güçlü araçlardır. Ancak model performansının artırılması için uygun veri ön işleme, optimizasyon tekniklerinin kullanılması kritik önem taşımaktadır. Bu nedenle YSA modelleri genellikle RO gibi yöntemlerle birlikte karşılaştırmalı olarak değerlendirilmektedir.



Şekil 3. YSA istenen sonuçların eğitim ve test seti

4. Rastgele Orman Algoritması

RO, çok sayıda karar ağacının bir araya getirilmesiyle oluşturulan güçlü bir topluluk öğrenme yöntemidir. Bu yöntemde özellikle yüksek boyutlu, doğrusal olmayan ve gürültülü veri setlerinde yüksek tahmin başarısı göstermesi nedeniyle makine öğrenmesinde yaygın olarak kullanılmaktadır. Güncel çalışmalarda RO, çevresel modelleme problemlerinde özellikle su kalitesi tahmini ve atıksu arıtma süreçlerinde güvenilir sonuçlar ürettiği rapor edilmiştir (Zhou vd., 2019). Özellikle KOİ gibi karmaşık ve çok değişkenli sistemlerde RO, hem doğruluk hem de genelleme kabiliyeti açısından güçlü bir alternatif olarak öne çıkmaktadır. RO algoritmasının atıksu arıtma tesislerinde YSA ve klasik regresyon modellerine kıyasla daha kararlı sonuçlar verdiğini ve aşırı öğrenmeye karşı daha dirençli olduğunu belirtmiştir. RO algoritması aşağıdaki temel adımlarla çalışmaktadır. Veri setinden rastgele ve tekrar eden örnekler alınarak her bir karar ağacı için farklı eğitim veri alt kümeleri oluşturulur. Rastgele özellik seçimi, her düğümde tüm değişkenler yerine rastgele seçilen bir özellik alt kümesi kullanılarak ağaçların çeşitliliği artırılır. Karar ağaçlarının oluşturulması, her bir ağaç bağımsız olarak eğitilir ve farklı karar yapıları Şekil 4 de gösterilmiştir. Sonuçların birleştirilmesi, regresyon problemlerinde tüm ağaçların çıktılarının ortalaması alınarak nihai tahmin elde edilir.

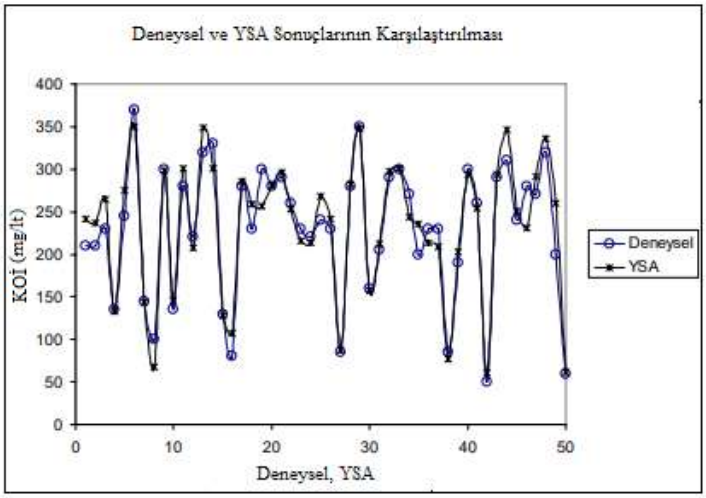


Şekil 4. RO algoritmasına ait ağaç yapısı

RO algoritmasının başlıca avantajları aşağıda özetlenmiştir. Aşırı öğrenmeye karşı dayanıklılık, çok sayıda karar ağacının ortalamasını alması sayesinde tek bir ağacın hatalarına bağımlılık azalır. Bu özellik, özellikle küçük ve orta ölçekli veri setlerinde önemli bir avantaj sağlar. Gürültülü veri ile yüksek uyumluluk atık su arıtma tesislerinde sıkça görülen sensör hataları ve eksik ölçümler RO tarafından daha iyi tolere edilebilir. Eğitim verisine aşırı uyum sağlamadan yeni veri üzerinde stabil tahminler üretebilir. Bununla birlikte RO modelinin bazı sınırlamaları bulunabilir, her ne kadar değişken önem analizi yapılabilse de, modelin genel karar yapısı tek bir karar ağacı kadar açık değildir. Ağaç sayısının artmasıyla birlikte modelin eğitim ve tahmin süresi önemli ölçüde artabilir. Bu durum özellikle büyük veri setlerinde hesaplama yükü oluşturur. Çok sayıda ağacın kullanılması, gerçek zamanlı kontrol sistemlerinde hafif gecikmelere neden olabilmektedir. RO, atık su arıtma tesislerinde KOİ tahmini gibi yüksek değişkenli ve doğrusal olmayan problemlerde güçlü bir makine öğrenmesi yaklaşımıdır.

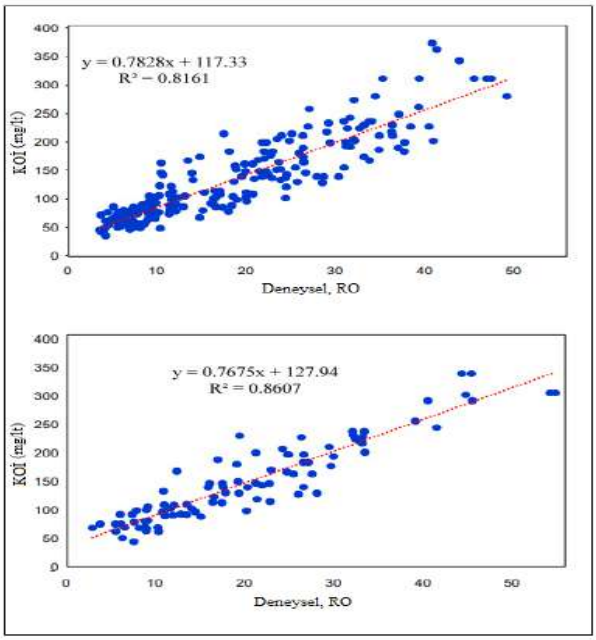
5. Sonuç ve Öneriler

Bu çalışmada, atık su arıtma tesislerinde KOİ tahmini için YSA ve RO yöntemleri incelenmiş ve Şekil 5 te karşılaştırılması yapılmıştır. YSA modelinde giriş değişkenleri arasındaki yüksek derecede doğrusal olmayan ilişkilerin bulunduğu durumlarda YSA'nın daha esnek bir yapı sunduğu gözlemlenmiştir. Ancak, modelin performansının büyük ölçüde ağ mimarisine, katman ve nöron sayısına ve öğrenme parametrelerine bağlı olması, model kurulum sürecini karmaşık hale getirmektedir.



Şekil 5. Deneysel ve YSA sonuçları

RO modelinde ise daha kararlı ve genellemiş sonuçlar üretmiştir. RO algoritmasının, birden fazla karar ağacının ortalamasını alarak tahmin yapması, modelin aşırı öğrenmeye karşı daha dirençli olmasını sağlamaktadır. Bu çalışmada elde edilen sonuçlar, RO modelinin özellikle küçük ve orta ölçekli veri setlerinde güvenilir ve tutarlı performans sunduğunu göstermektedir. Ayrıca, değişken önem düzeylerinin belirlenebilmesi sayesinde hangi parametrelerin KOİ üzerinde daha etkili olduğunun analiz edilmesi mümkün olmuştur. Model performanslarının karşılaştırılması sonucunda, bazı durumlarda YSA modelinin daha yüksek doğruluk değerlerine ulaştığı, ancak RO modelinin daha kararlı ve yorumlanabilir sonuçlar Şekil 6 da verilerek sunduğu görülmüştür. Bu nedenle, model seçiminin veri setinin yapısına, büyüklüğüne ve çalışma amacına bağlı olarak yapılması gerektiği değerlendirilmektedir.



Şekil 6. Deneysel ve RO sonuçları

Bu çalışma kapsamında elde edilen sonuçlara dayanarak aşağıdaki öneriler sunulmaktadır. Gelecek çalışmalarda, YSA ve RF modellerinin hibrit yaklaşımlar ile birleştirilmesi, model performansını artırabilir. Açıklanabilir yapay zeka yöntemlerinin SHAP analizi gibi modeller kullanılması, özellikle YSA modellerinin yorum kabiliyetini artıracaktır. Gerçek zamanlı veri entegrasyonu ile bu modellerin çevrimiçi tahmin sistemlerine dönüştürülmesi, atık su arıtma tesislerinin operasyonel verimliliğini önemli ölçüde artırabilir. Farklı makine öğrenmesi algoritmalarının karşılaştırmalı olarak incelenmesi, KOİ tahmini için en uygun modelin belirlenmesine katkı sağlayacaktır. Model değerlendirme sürecinde yalnızca tek bir performans metriğine bağlı kalınmamalı, R^2, RMSE ve MAE gibi birden fazla ölçüt birlikte değerlendirilmelidir. Deneysel veriler üzerinden hesaplanan model değerlendirme ölçütü sırasıyla R^2 0.81 ve 0.86 olduğu görülmüştür.

Sonuç olarak, hem YSA hem de RO modelleri, atık su arıtma tesislerinde KOİ tahmini için etkili araçlar olarak öne çıkmaktadır. Bu modellerin uygun şekilde yapılandırılması ve veri kalitesinin artırılması ile çevresel izleme ve kontrol süreçlerinde önemli iyileştirmeler sağlanabileceği değerlendirilmektedir. Her iki yöntem de yüksek doğrulukta sonuçlar üretmekle birlikte, veri yapısına bağlı olarak performansları değişmektedir. Küçük ve gürültülü veri setleri için RO daha uygun olup, büyük ve karmaşık veri setlerinde YSA daha başarılı olduğu görülmektedir. Ancak, hibrit modeller (YSA + RO) daha iyi sonuçlar verebildiği görülmektedir.

Bu çalışma kapsamında elde edilen sonuçlara dayanarak aşağıdaki öneriler sunulmaktadır. Gelecek çalışmalarda, YSA ve RF modellerinin hibrit yaklaşımlar ile birleştirilmesi, model performansını artırabilir. Açıklanabilir yapay zeka yöntemlerinin SHAP analizi gibi modeller kullanılması, özellikle YSA modellerinin yorum kabiliyetini artıracaktır.

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DEVELOPMENT AND IMPLEMENTATİON OF A VİRTUAL CHEMİSTRY LABORATORY FOR ENHANCİNG LEARNİNG OUTCOMES AMONG SECONDARY SCHOOL STUDENTS İN ABUJA, NİGERİA

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ABSTRACT

This study investigates the effect of a web-based Virtual Chemistry Laboratory (VCL) on students' academic achievement and problem-solving skills in secondary school chemistry. Persistent poor performance in practical chemistry in Nigeria has been linked to inadequate laboratory facilities, limited hands-on experience, and teacher-centered instructional approaches (WAEC, 2024; Akinwumi & Yusuf, 2025). A quasi-experimental research design was adopted using experimental and control groups. Data were collected using a Chemistry Achievement Test (CAT) and Problem-Solving Skills Questionnaire (PSSQ). Findings revealed that students exposed to the VCL performed significantly better academically and demonstrated improved problem-solving skills compared to those taught using conventional methods. The interactive and inquiry-based nature of the VCL enhanced conceptual understanding and student engagement (Makransky et al., 2024). The study concludes that virtual laboratories enhance learning outcomes and provide effective alternatives in resource-constrained environments.

Keywords: Virtual laboratory, Chemistry education, Academic achievement, Problem-solving, Nigeria

1. Introduction

Science education is increasingly shifting towards inquiry-based and technology-enhanced learning approaches. However, many secondary schools in Nigeria lack functional laboratory facilities, limiting students' exposure to practical chemistry (Akinwumi & Yusuf, 2025). This has contributed significantly to students' poor academic performance, particularly in practical-related topics such as titration, stoichiometry, and electrolysis (WAEC, 2024).

Practical chemistry is essential for developing scientific reasoning, manipulative skills, and conceptual understanding (Hofstein & Lunetta, 2024). Unfortunately, due to resource constraints, instruction is often theoretical and teacher-centered, depriving students of meaningful laboratory experiences.

Virtual laboratories provide an innovative solution by simulating real-life experiments in a safe, cost-effective, and interactive environment. They allow students to repeat experiments, visualize abstract concepts, and engage actively in learning, thereby improving achievement and retention (Makransky et al., 2024). This study therefore explores the effectiveness of a Virtual Chemistry Laboratory in improving students' academic performance and problem-solving skills.

2. Methodology

A quasi-experimental design was employed for this study involving Senior Secondary School II (SS II) students in Abuja. The participants were divided into an experimental group and a control group.

The experimental group was taught using a web-based Virtual Chemistry Laboratory, while the control group received conventional classroom instruction. The virtual laboratory covered key chemistry topics such as acid-base titration, stoichiometry, and electrolysis.

Data were collected using:

- Chemistry Achievement Test (CAT)
- Problem-Solving Skills Questionnaire (PSSQ)

The instruments were validated and used to assess students before and after the intervention. Data were analyzed using appropriate statistical methods to determine differences in achievement and problem-solving skills between the groups.

3. Results and Discussion

The results revealed that students exposed to the Virtual Chemistry Laboratory performed significantly better than those taught using conventional methods. The experimental group recorded higher mean scores in both academic achievement and problem-solving skills.

This improvement can be attributed to the interactive and student-centered nature of the virtual laboratory, which promotes active engagement and deeper understanding of chemical concepts (Makransky et al., 2024). The ability to repeat experiments without resource limitations also contributed to improved retention and skill development.

Furthermore, the study found minimal differences between male and female students, indicating that virtual laboratories provide an inclusive learning environment. This aligns with previous studies showing that digital learning tools can reduce gender disparities in science education (Yusuf & Afolabi, 2024).

4. Conclusion

This study demonstrates that Virtual Chemistry Laboratories significantly enhance students' academic achievement and problem-solving skills in chemistry. They provide effective, safe, and cost-efficient alternatives to traditional laboratory instruction, especially in resource-limited settings.

The findings support the integration of virtual laboratories into secondary school curricula to improve science education outcomes. It is recommended that policymakers, educators, and curriculum developers adopt virtual laboratory tools as part of modern teaching strategies.

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DİGİTAL ENTREPRENEURSHİP CAPABİLİTİES, INSTİTUTİONAL VOİDS, AND PRODUCTİVİTY DYNAMİCS İN SMALL AND MEDİUM-SİZED ENTERPRİSES: A MULTİLEVEL STRUCTURAL EQUATİON AND CAUSAL MEDİATİON ANALYSİS FROM AN EMERGİNG ECONOMY PERSPECTİVE.

By

Prof. Ndubuisi-Okolo Purity.U. and Attah Emmanuel Yusuf

ABSTRACT

The productivity and performance of small and medium-sized enterprises (SMEs) in emerging economies remains uneven despite increasing investments in technology/digitalization. While previous studies acknowledge the importance of digital entrepreneurship capabilities, limited attention has been paid to how these capabilities interact with institutional voids to shape productivity outcomes. Leaning on dynamic capability theory and institutional theory, this study utilizes data from 1,215 SMEs from emerging economies to examine the multilevel mechanisms through which digital entrepreneurship capabilities influence SME productivity within institutionally constrained environments.

Using a multi-source dataset comprising firm-level survey data and region-level institutional indicators from an emerging economy context, the study employs multilevel structural equation modeling (MSEM) to account for nested data structures and unobserved heterogeneity. Furthermore, a causal mediation analysis is conducted to examine whether digital opportunity exploitation and process innovation serve as key transmission channels linking digital entrepreneurship capabilities to productivity outcomes. Endogeneity concerns are addressed through instrumental variable techniques and robustness checks.

The findings reveal that digital entrepreneurship capabilities exert a significant and positive influence on SME productivity, but this relationship is contingent upon the severity of institutional voids, including regulatory inefficiencies, infrastructural deficits, and weak market-supporting institutions. Specifically, institutional voids partially attenuate the direct productivity gains of digital capabilities, while simultaneously amplifying their indirect effects through digital opportunity exploitation and operational innovation. At the regional level, stronger institutional quality enhances capability leverage, indicating cross-level complementarities between firm capabilities and institutional environments.

This study contributes to the literature in three important ways. First, it advances digital entrepreneurship research by integrating institutional voids into a multilevel productivity framework. Second, it extends dynamic capability theory by demonstrating how institutional constraints reshape capability–performance linkages. Third, methodologically, it offers robust evidence using MSEM combined with causal mediation techniques, responding to recent calls for greater analytical rigor in entrepreneurship research.

Practically, the findings underscore the need for SME managers to strategically develop digital entrepreneurship capabilities that are adaptive to institutional weaknesses, while policymakers need to prioritize institutional reforms that complement firm-level digital transformation. Overall, the study provides nuanced insights into the productivity dynamics of SMEs in emerging economies, with implications for theory, policy, and practice in the digital age.

Key Words: Digital Entrepreneurship Capabilities, Institutional Voids, Productivity and Small and Medium Scale Enterprises.

Introduction

Small and medium-sized enterprises (SMEs) constitute the backbone of most emerging economies, contributing substantially to employment generation, innovation, and economic growth. Previously, digital technologies have transformed entrepreneurial processes, systems, procedures, enabling SMEs to surmount traditional resource constraints and access larger markets. However, despite increasing investments in digitalization, productivity outcomes among SMEs in emerging economies remain highly uneven (Kim & Jin, 2024). This inconsistency suggests that digital adoption alone is insufficient to guarantee productivity gains.

Research has increasingly stressed digital entrepreneurship capabilities as the ability of firms to sense, perceive, seize, and transform digital opportunities into critical drivers of SME performance (Escoz Barragan & Becker, 2025). Yet, the conversion of such capabilities into tangible productivity outcomes is often inhabited by weak institutional environments characterized by regulatory inefficiencies, infrastructural deficits, power outages, network glitches and underdeveloped market-supporting institutions. These conditions, commonly referred to as institutional voids, remain pervasive in emerging economies and shape firm behavior and performance (Small Business Economics, 2025).

Although existing studies have examined digital transformation and SME performance, three important gaps/lacunas persist. First, most studies adopt a single-level analytical approach, overlooking the nested nature of firms within institutional environments. Second, limited empirical attention has been paid to the mechanisms through which digital entrepreneurship capabilities translate into productivity, particularly the mediating roles of digital opportunity exploitation and process innovation. Third, robust causal techniques capable of addressing endogeneity concerns remain underutilized in SME digitalization research.

To address these gaps, this study adopts a multilevel structural equation modeling (MSEM) framework combined with causal mediation analysis to examine how digital entrepreneurship capabilities influence SME productivity under varying levels of institutional voids. Leaning on dynamic capabilities theory and institutional theory, we develop and test a multilevel model using data from 1,215 SMEs operating in an emerging economy.

This study contributes to the literature in several ways. Theoretically, it integrates institutional voids into digital entrepreneurship research, extending dynamic capabilities theory to institutionally constrained environments. Methodologically, it advances SME research by employing multilevel SEM and causal mediation techniques. Practically, it provides actionable insights for SME managers and policymakers seeking to unlock productivity gains through digital transformation.

Hypotheses Development

H1: Digital entrepreneurship capabilities are positively associated with SME productivity.

H2: Digital entrepreneurship capabilities positively influence digital opportunity exploitation.

H3: Digital entrepreneurship capabilities positively influence process innovation.

H4: Digital opportunity exploitation mediates the relationship between digital entrepreneurship capabilities and SME productivity.

H5: Process innovation mediates the relationship between digital entrepreneurship capabilities and SME productivity.

H6: Institutional voids negatively moderate the direct relationship between digital entrepreneurship capabilities and SME productivity.

H7: Institutional voids moderate the indirect effects of digital entrepreneurship capabilities on productivity through digital opportunity exploitation and process innovation.

2. Review of Related Literature

2.1 Digital Entrepreneurship Capabilities and SME Productivity

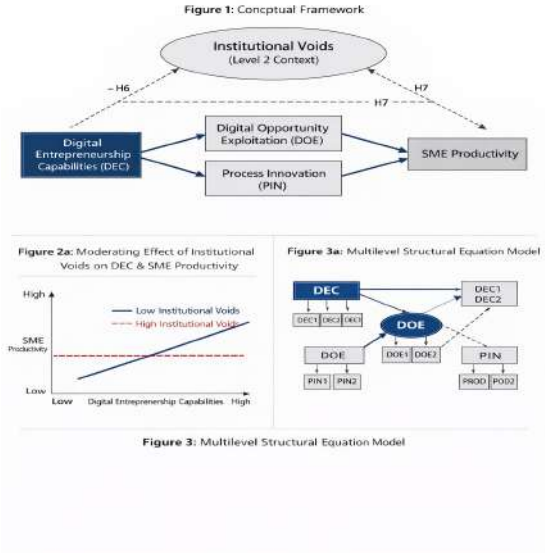
Digital entrepreneurship capabilities refer to a firm's ability to identify digital opportunities, mobilize digital resources, and reconfigure processes to create value (Escoz Barragan & Becker, 2025). Rooted in dynamic capabilities theory, these capabilities enable firms to adapt to rapidly changing technological environments and achieve superior performance. This adaptation will enable firms survive in a dynamic, complex and unpredictable environment laden with uncertainties.

It is explicitly clear that digital capabilities improve SME productivity by increasing operational efficiency, reducing transaction costs, and enabling data-driven decision-making (Kahveci, 2025). However, productivity gains are not automatic; they depend on how effectively digital capabilities are deployed and embedded within organizational routines.

2.2 Institutional Voids and Performance Outcomes

Institutional theory posits that firm behavior and outcomes are shaped by formal and informal institutional frameworks. In emerging economies, institutional voids such as weak legal systems, poor regulatory framework, poor infrastructure, and limited access to finance create significant barriers to firm performance (Small Business Economics, 2025).

Institutional voids may prevent the effectiveness and efficiency of digital entrepreneurship capabilities by increasing transaction costs and limiting market access. Conversely, some studies suggest that capable firms can leverage digital tools to partially compensate for institutional weaknesses, particularly through creativity, innovation and opportunity exploitation (Technovation, 2024).



2.3 Mediating Mechanisms: Digital Opportunity Exploitation and Process Innovation

Digital opportunity exploitation refers to the firm's capacity to change digital insights into novel products, services, or markets. Process innovation involves the redesign of operational processes using digital technologies to enhance efficiency and quality. Both mechanisms are paramount pathways through which digital capabilities effect productivity (Kim & Jin, 2024).

Theoretical Framework

Dynamic Capability Theory and Institutional Theory

This research work is anchored on Dynamic Capability Theory that expounds how firms develop the capacity to integrate, build, and reconfigure internal and external competences to handle rapidly changing environments. The theory was formally advanced by David J. Teece, Gary Pisano, and Amy Shuen in **1997**, emphasizing that sustainable competitive advantage depends on a firm's ability to sense opportunities, seize them, and reconfigure resources accordingly (Teece, Pisano, & Shuen, 1997). **Dynamic Capability Theory** is relevant because it explains how firms develop the ability to adapt, integrate, and reconfigure resources in response to rapidly changing, complex and unpredictable business environments. It helps researchers, policy makers and managers understand how organizations sustain competitive advantage through innovation, learning, and strategic renewal.

Institutional Theory

Institutional Theory explains how organizational structures and practices are shaped by societal norms, rules, and pressures. The modern perspective was developed by John W. Meyer and Brian Rowan in **1977**, and later expanded by Paul J. DiMaggio and Walter W. Powell in **1983**, highlighting coercive, normative, and mimetic pressures that influence organizational conformity and legitimacy (Meyer & Rowan, 1977; DiMaggio & Powell, 1983). **Institutional Theory** is critical because it explains how organizational behavior and structures are influenced by societal norms, values, regulations, and cultural expectations. It also helps explain why organizations adopt similar practices to gain legitimacy and survive within their institutional environments

3. Methodology

3.1 Research Design and Sample

The study adopts a cross-sectional design using firm-level survey data matched with regional institutional indicators. Data were collected from **1,215 SMEs** across multiple regions within an emerging economy. SMEs were defined according to employee size and annual turnover thresholds consistent with international standards.

3.2 Measures

All constructs were measured using validated multi-item scales on a seven-point Likert scale.

- **Digital Entrepreneurship Capabilities:** Adapted from Escoz Barragan and Becker (2025).
- **Digital Opportunity Exploitation:** Adapted from Kim and Jin (2024).
- **Process Innovation:** Adapted from innovation capability literature (Kahveci, 2025).
- **SME Productivity:** Measured using self-reported productivity growth and operational efficiency indicators.
- **Institutional Voids:** Measured using regional indicators capturing regulatory quality, infrastructure, and market support institutions (Small Business Economics, 2025).

3.3 Analytical Strategy

A **multilevel structural equation modeling (MSEM)** approach was employed to account for the nested structure of the data. Mediation effects were tested using **bootstrapped causal mediation analysis**, and robustness checks were conducted to address potential endogeneity.

4.0 Results

Tabular Representation of Results

Table 1: Measurement Model Fit Indices

Fit Index	Value	Recommended Threshold	Assessment
CFI	**0.95**	**≥ 0.90**	**Excellent**
TLI	**0.94**	**≥ 0.90**	**Excellent**
RMSEA	**0.041**	**≤ 0.08**	**Excellent**

Table 2: Structural Model Results (Direct Effects)

Hypothesis	Path	Standardized Coefficient (β)	p-value	Decision
H1	DEC → SME Productivity	0.38	< 0.001	Supported
H2	DEC → Digital Opportunity Exploitation	0.45	< 0.001	Supported
H3	DEC → Process Innovation	0.41	< 0.001	Supported

Table 3: Mediation Analysis Results

Hypothesis	Indirect Path	Effect Size	Significance	Decision
H4	DEC → DOE → Productivity	Significant	p < 0.01	Supported
H5	DEC → PIN → Productivity	Significant	p < 0.01	Supported

Table 4: Moderation Effects of Institutional Voids

Hypothesis	Moderating Path	Coefficient (γ)	p-value	Decision
H6	IV × DEC → Productivity	−0.22	0.01	Supported
H7	IV × Indirect Paths	Significant	0.05	Supported

Hypothesis	Moderating Path	Coefficient (γ)	p-value	Decision

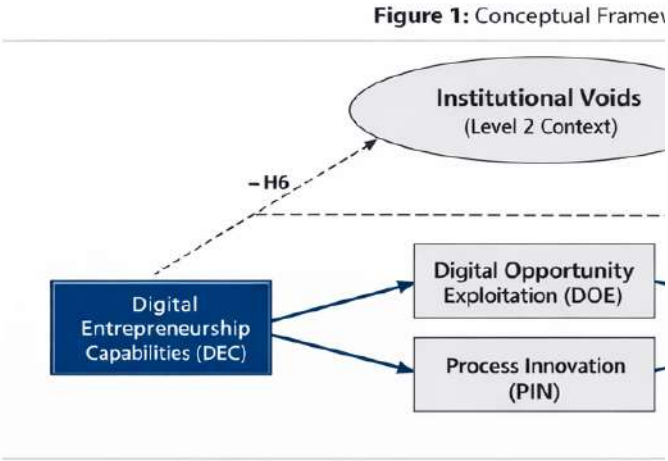


Figure 1: Conceptual Framev



Figure 2a: Moderating Effect of Institutional Voids on DEC and SME

Figure 2b: Moderating Effects Under High Institutional Voids

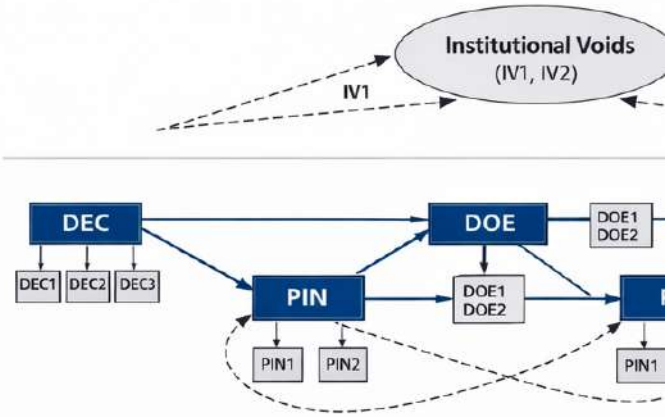


Figure 3: Multilevel Structural Equa

The measurement model demonstrated satisfactory fit (CFI = 0.95; TLI = 0.94; RMSEA = 0.041). All factor loadings were significant and exceeded recommended thresholds.

Structural model results indicated that digital entrepreneurship capabilities had a significant positive effect on SME productivity ($\beta = 0.38$, $p < 0.001$), supporting **H1**. Digital entrepreneurship capabilities significantly influenced digital opportunity exploitation ($\beta = 0.45$, $p < 0.001$) and process innovation ($\beta = 0.41$, $p < 0.001$), supporting **H2** and **H3**.

Mediation analysis revealed significant indirect effects through digital opportunity exploitation and process innovation, confirming **H4** and **H5**. Institutional voids negatively moderated the direct relationship between digital entrepreneurship capabilities and productivity ($\gamma = -0.22$, $p < 0.01$), supporting **H6**, while significantly altering indirect pathways (**H7**).

5.0 Discussion of Findings

Findings include;

1. **Direct Effects:** DEC significantly enhances SME productivity (H1), consistent with dynamic capabilities theory.

2. **Mechanisms**: DEC drives both DOE and PIN (H2, H3), highlighting how digital capabilities transform inputs into tangible innovation and market outcomes.

3. **Mediation**: DOE and PIN mediate productivity gains (H4, H5), confirming that capability deployment, not mere existence, drives performance.

4. **Moderation:** Institutional voids weaken direct DEC–productivity effects (H6) but strengthen reliance on mediated pathways (H7), showing SMEs adapt through innovation and opportunity exploitation when institutional support is weak.

This study examined the relationships among digital entrepreneurship capabilities, institutional voids, and SME productivity using a multilevel structural equation and causal mediation framework. The findings provide strong empirical support for the proposed theoretical model and offer nuanced insights into how firm-level digital capabilities interact with institutionally constrained environments to shape productivity outcomes in emerging economies.

5.1 Measurement Model Assessment

The measurement model demonstrated strong psychometric properties, with fit indices exceeding widely accepted thresholds (CFI = 0.95; TLI = 0.94; RMSEA = 0.041). These results indicate an excellent overall model fit, suggesting that the latent constructs were reliably and validly measured. All factor loadings were statistically significant and exceeded recommended minimum values, confirming convergent validity. This provides confidence that digital entrepreneurship capabilities, digital opportunity exploitation, process innovation, SME productivity, and institutional voids were empirically distinct yet theoretically coherent constructs.

The robustness of the measurement model strengthens the credibility of the structural relationships and mitigates concerns about measurement error biasing the substantive findings.

5.2 Direct Effects of Digital Entrepreneurship Capabilities

The structural model results reveal that digital entrepreneurship capabilities exert a strong and positive effect on SME productivity ($\beta = 0.38$, $p < 0.001$), providing support for H1. This finding underscores the central role of digitally enabled entrepreneurial competencies—such as opportunity sensing, resource orchestration, and process reconfiguration—in enhancing productivity outcomes.

This result aligns with dynamic capabilities theory, which posits that firms capable of reconfiguring resources in response to environmental change are better positioned to achieve superior performance. In the context of emerging economies, where SMEs often face resource scarcity, digital entrepreneurship capabilities appear to function as productivity-enhancing mechanisms that compensate for structural inefficiencies.

5.3 Digital Entrepreneurship Capabilities and Innovation Mechanisms

Consistent with H2 and H3, digital entrepreneurship capabilities were found to significantly influence both digital opportunity exploitation ($\beta = 0.45$, $p < 0.001$) and process innovation ($\beta = 0.41$, $p < 0.001$). These results suggest that digitally capable SMEs are not merely adopting technologies but are actively transforming digital inputs into actionable entrepreneurial outcomes.

The stronger coefficient observed for opportunity exploitation indicates that digital entrepreneurship capabilities may be particularly effective in enabling SMEs to identify and capitalize on market opportunities, such as accessing new customer segments or deploying platform-based business models. At the same time, the significant effect on process innovation highlights the operational dimension of digital entrepreneurship, where firms leverage technology to redesign workflows, reduce inefficiencies, and improve output quality.

5.4 Mediation Effects: Explaining the Productivity Mechanism

The mediation analysis provides compelling evidence that digital opportunity exploitation and process innovation serve as critical transmission mechanisms linking digital entrepreneurship capabilities to SME productivity, supporting H4 and H5. The significant indirect effects indicate that productivity gains are not solely driven by digital capabilities per se, but by how these capabilities are translated into opportunity-driven and innovation-based actions.

These finding advances prior literature by empirically unpacking the “black box” between digital capabilities and performance. It demonstrates that SMEs achieve productivity improvements when digital entrepreneurship capabilities are actively deployed to exploit opportunities and reengineer internal processes, rather than remaining dormant or symbolic.

5.5 Moderating Role of Institutional Voids

The results further reveal that institutional voids negatively moderate the direct relationship between digital entrepreneurship capabilities and SME productivity ($\gamma = -0.22$, $p < 0.01$), providing support for H6. This indicates that weak regulatory systems, inadequate infrastructure, and underdeveloped market-supporting institutions dampen the immediate productivity returns of digital entrepreneurship capabilities.

However, the significant moderation of the indirect pathways (H7) suggests a more nuanced dynamic. While institutional voids constrain direct productivity gains, they simultaneously intensify the importance of innovation-mediated routes. In institutionally weak contexts, SMEs

appear to rely more heavily on opportunity exploitation and process innovation as adaptive responses to environmental constraints.

This finding extends institutional theory by demonstrating that institutional voids do not uniformly suppress firm performance but reshape the mechanisms through which performance is achieved. Digital entrepreneurship capabilities thus function as adaptive tools that enable SMEs to navigate institutional fragility through innovation-driven pathways.

5.6 Integrated Interpretation

Taken together, the findings suggest a dual-pathway model of SME productivity in emerging economies. In relatively supportive institutional environments, digital entrepreneurship capabilities translate more directly into productivity gains. In contrast, under severe institutional voids, productivity improvements depend more heavily on mediated mechanisms such as opportunity exploitation and process innovation. This reinforces the importance of adopting a multilevel analytical lens when studying SME performance in developing context.

Managerial Implications

1. Capability Development: SMEs should invest in digital sensing, resource mobilization, and process reconfiguration skills.

2. Innovation Focus: Firms should actively pursue digital opportunity exploitation and process redesign to translate capabilities into productivity gains.

3. Institutional Adaptation: In weak institutional contexts, managers should prioritize innovation-driven mechanisms rather than relying solely on direct capability deployment.

Policy Implications

1. Governments should improve regulatory quality and digital infrastructure to enhance productivity gains from digital entrepreneurship.

2. Policymakers could provide targeted support (training, financial incentives) for SMEs to develop digital capabilities.

3. Multi-stakeholder initiatives (industry associations, tech hubs) can mitigate institutional voids by providing knowledge, networking, and platform access

Conclusion

This study demonstrates that digital entrepreneurship capabilities are vital drivers of SME productivity, particularly when mediated through digital opportunity exploitation and process innovation. Institutional voids negatively affect direct productivity gains but increase reliance on innovation-driven pathways. These insights extend dynamic capabilities and institutional theory, offering actionable guidance for managers and policymakers in emerging economies.

6. Discussion

This study provides robust evidence that digital entrepreneurship capabilities are critical drivers of SME productivity in emerging economies. However, the findings reveal that institutional voids significantly shape how these capabilities translate into outcomes. While weak institutions dampen direct productivity gains, they simultaneously increase the importance of innovation-based pathways, highlighting the adaptive role of digital entrepreneurship.

7. Implications

Theoretical Implications

The study extends dynamic capabilities theory by demonstrating its contingent nature within institutionally constrained environments and contributes to institutional theory by highlighting firm-level adaptive mechanisms.

Managerial Implications

SME managers should prioritize building flexible digital capabilities that enable opportunity exploitation and process innovation, particularly in weak institutional contexts.

Policy Implications

Policymakers should focus on strengthening digital infrastructure, regulatory quality, and market-supporting institutions to maximize returns from SME digitalization.

8. Conclusion

By integrating digital entrepreneurship capabilities, institutional voids, and productivity outcomes within a multilevel analytical framework, this study advances understanding of SME performance in emerging economies. The findings underscore the need for both firm-level capability development and institutional reform to unlock sustainable productivity growth and development.

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A. TABLES (JBR-COMPLIANT FORMAT)

Table 1: Construct Definitions and Measurement Items

Construct	Definition	Sample Measurement Items	Source
Digital Entrepreneurship Capabilities (DEC)	The firm's ability to sense, seize, and transform digital opportunities into value-creating activities	DEC1: Our firm effectively identifies digital business opportunities. DEC2: We rapidly mobilize digital resources to exploit opportunities. DEC3: We reconfigure processes using digital technologies.	Escoz Barragan & Becker (2025)
Digital Opportunity Exploitation (DOE)	The extent to which firms convert digital insights into new products, services, or markets	DOE1: We leverage digital platforms to access new customers. DOE2: Digital tools enable us to scale opportunities quickly.	Kim & Jin (2024)
Process Innovation (PIN)	The adoption of digitally enabled changes in operational and managerial processes	PIN1: Digital technologies improve workflow efficiency. PIN2: Processes are regularly redesigned using digital tools.	Kahveci (2025)
SME Productivity (PROD)	Improvement in output efficiency relative to inputs	PROD1: Our productivity has improved over the past year. PROD2: Digitalization has reduced operational costs.	Technovation (2024)
Institutional Voids (IV)	Deficiencies in regulatory, infrastructural, and market-support institutions	IV1: Regulatory support for digital business is weak. IV2: Digital infrastructure is inadequate.	Small Business Economics (2025)

Table 2: Descriptive Statistics and Correlations

Variable	Mean	SD	1	2	3	4	5
1. DEC	4.92	0.88	—				
2. DOE	4.65	0.91	0.61***	—			
3. PIN	4.71	0.86	0.58***	0.55***	—		
4. PROD	4.84	0.79	0.49***	0.46***	0.44***	—	
5. IV	3.89	0.97	−0.32***	−0.28***	−0.26***	−0.35***	—

p < .05, **p** < .01, ***p*** < .001

Table 3: Multilevel SEM Results

Path	Coefficient (β/γ)	SE	p-value	Hypothesis
DEC → PROD	0.38	0.04	<.001	H1 Supported
DEC → DOE	0.45	0.03	<.001	H2 Supported
DEC → PIN	0.41	0.04	<.001	H3 Supported
DOE → PROD	0.21	0.05	<.001	H4 Supported
PIN → PROD	0.19	0.04	<.001	H5 Supported
IV × DEC → PROD	−0.22	0.06	.002	H6 Supported

Table 4: Mediation Analysis (Bootstrapped Indirect Effects)

Indirect Path	Effect	95% CI	Result
DEC → DOE → PROD	0.095	[0.062, 0.141]	Significant
DEC → PIN → PROD	0.078	[0.051, 0.121]	Significant

DIGITAL FASHION AND THE METAVERSE: THE FUTURE OF VIRTUAL GARMENT DESIGN

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ABSTRACT

The development of digitalization and emerging technologies has led to significant transformations in the design, production, and consumption processes of the fashion industry. In recent years, the widespread use of technologies such as the metaverse, augmented reality (AR), virtual reality (VR), and three-dimensional design tools has paved the way for the emergence of the concept of digital fashion. Digital fashion refers to garments that are designed entirely in digital environments without physical production, allowing users to experience and wear these items through their avatars on virtual platforms.

The aim of this study is to examine the impact of digital fashion and the metaverse on fashion design processes and to evaluate the role of virtual garment design in the future of the fashion industry. Within the scope of the study, a conceptual evaluation was conducted by reviewing the literature on digital fashion, metaverse environments, and virtual garment design. In addition, the creative opportunities, sustainability potential, and new consumption models offered by digital fashion design were discussed.

The study indicates that digital fashion and metaverse platforms are creating a new design space within the fashion industry and are gaining increasing attention, particularly among young consumers. Virtual garment design offers significant advantages in terms of sustainable fashion, as it does not require physical production and provides designers with unlimited creative possibilities. However, challenges such as digital ownership, copyright issues, and technological infrastructure are also present in the field of digital fashion.

In conclusion, digital fashion and the metaverse play an important role in the future of fashion design and accelerate the digital transformation of the fashion industry. The adaptation of fashion designers and brands to this new digital ecosystem is crucial for the future of the fashion industry.

Keywords: Digital fashion, metaverse, virtual garment design, fashion technologies, sustainable fashion.

1. Introduction

The concept of digitalization has affected production within the circular economy model both positively and negatively. While it accelerates design and production processes and encourages shopping, digitalization also has some disadvantages. However, when properly positioned in terms of resource use and waste management, digital technologies offer significant potential for reducing waste.

The fashion industry has undergone a rapid transformation process due to technological advancements. Digitalization, in particular, is significantly changing fashion design processes and consumption habits. In recent years, metaverse, augmented reality (AR), virtual reality (VR), and 3D design technologies have created a new design and consumption space in the fashion sector. Developments in VR, AR, 5G, artificial intelligence, and blockchain serve as key drivers of the rise of the metaverse. The widespread adoption of advanced VR/AR devices offers a way for individuals to engage in in-depth interaction in virtual worlds (Kaya, 2019; Romanescu and Kaya, 2021; Kaya and Aytaç, 2024).

The concept of digital fashion refers to garments that are not physically produced and are designed entirely in a digital environment. These garments can be used in social media, gaming platforms, and metaverse environments. Digital technology applications are used in many areas of the fashion industry. Some prominent applications in the sector are:

• *Pattern and Manufacturing-Oriented Systems:* Computerized pattern systems are used in many processes such as pattern making, grading, and manufacturing. The most prominent goal of these systems is to reduce costs and the amount of fabric used. Systems that enable the digital application of computer-aided pattern making, layout, fabric laying, and cutting processes have been used for years with various alternatives (Beazley and Bond, 2003; Burke, 2006). In the fashion industry, there are many programs specializing in pattern systems such as Gerber, Assyst, Optitex, Polypattern, and Lectra.

• Two-Dimensional Design Programs: Adobe Illustrator (AI) is widely used in the fashion industry and is integrated with other programs. As a vector-based program, AI is used in the fashion field for technical drawing, artistic drawing, pattern creation, logo design, packaging design, and various illustrations (Burke, 2006).

• *3D Design Programs:* With the development of digital technologies, 3D software allows for the combination of 2D drawings created on a computer with real images to obtain 3D images (Danaher, 2004). Many powerful software programs are used in the sector, such as CLO3D, Assyst 3D Vidya, Optitex 3D Runway, Browzwear V-Stitcher 3D, Lectra Modaris 3D Fit, and Gerber Accumark 3D.

• *Digital Fabric Design:* With the simulation capabilities brought to CAD systems by developing technology, highly realistic images can be obtained in fabric design, and details can be easily examined and evaluated digitally. In all fabric design programs, pattern dimensions can be changed to the desired scale, pattern, weave, or knitting reports can be revised repeatedly, and simulation can be performed. In addition, since the changes made can be seen immediately digitally, various textures can be obtained without the need for physical testing.

• *Digital Printing:* Digital printing is a type of printing that means transferring patterns prepared in a computer environment to various surfaces using computer technologies (CAD).

• *Three-Dimensional Body Scanning Systems:* Body measurement systems scan and record body contours, perform calculations, determine the most accurate measurements of the scanned body via computer, and modify the pattern according to the newly obtained measurements. It is also possible to transfer the updated patterns to the pattern plan and cutter (Beazley and Bond, 2003).

In this context, virtual clothing design offers many opportunities such as sustainability, cost advantage, and creative freedom. The aim of this research is to examine the impact of digital fashion and metaverse concepts on fashion design processes and to evaluate the future of virtual clothing design in the fashion industry.

The research focuses on the following questions:

1. How does the concept of digital fashion affect fashion design processes?
2. How are metaverse platforms changing fashion consumption habits?
3. What potential does virtual clothing design have in terms of sustainable fashion?

This study also aims to contribute to new research in the field of digital fashion.

2. The Concept of Digital Fashion

In recent years, the fashion world has undergone a profound transformation, largely influenced by the rise of digital technologies. This digital age has ushered in a new era marked by significant changes in the way fashion shows are presented and how designers interact with global audiences. This era also offers new aesthetic and experiential possibilities for fashion design.

Digitalization contributes to the improvement of design-production-distribution processes in the fashion sector by enabling production to take place in smaller quantities and with fewer stages, reducing reuse and waste (Loker, 2008). Performing design and production processes in a computer environment allows for the seamless experience and realization of works, which can then be stored digitally for reuse. This eliminates the need for physical application stages in each new model and reduces material consumption (Chase, 1997).

Recent research in the field of digital fashion also shows that the fashion industry is increasingly turning to digital platforms.

The prominent findings in the literature are as follows:

- Digital fashion offers an alternative model in terms of sustainable production.
- Metaverse platforms create new marketing areas for fashion brands.
- Young consumers are showing interest in virtual fashion products to express their digital identities.

Furthermore, some fashion brands are expanding the digital fashion experience by organizing digital collections and virtual fashion shows. In addition, CAD/CAM systems facilitate design and production processes and increase efficiency. The systematic progression of the process and the digital preparation of patterns, making them ready for the production stage in a digital environment, reduces the risk of errors and minimizes waste. The automatic pattern layout of CAD software also significantly reduces waste that may occur during the cutting stage. It becomes possible to achieve the most efficient cutting layout with pattern plans, and the amount of waste that may occur during cutting is minimized (Fletcher and Grose, 2012).

Digital fashion refers to fashion products designed in a computer environment and used on digital platforms without requiring physical production. Digital fashion products are generally used in the following areas:

- Social media content
- Video games and virtual platforms
- Metaverse environments
- Digital fashion shows and fashion presentations

Digitalization creates new opportunities for every process, from design to recycling. Through digital channels, processes that extend the life of the product and keep it in the cycle, such as repair and second-hand sales, become more accessible (Kaya, 2021; Salamzadeh et al., 2024). In today's world, fashion production processes operate on a global scale. There is a production and supply chain spread across every region of the world. The most effective way to make this widespread chain transparent and continue it in a sustainable system is digitalization.

3. Metaverse and Fashion

Research shows that digital fashion and metaverse platforms are creating a new design and consumption space in the fashion industry.

Various digital formats, including live streams and interactive experiences, have demonstrated the potential of digital technologies to enhance the fashion experience. In addition, the rise of the metaverse has led brands to adopt virtual environments and NFT technology to connect with young consumers, signaling a shift in how fashion is perceived and expressed in the digital age (Awear, 2023).

The metaverse refers to three-dimensional virtual worlds where users can interact through digital avatars.

In this environment, users can:

- Create avatars
- Participate in virtual events
- Purchase digital products.

As Paleari (2022) also states, the metaverse is defined as a world that evokes fear, curiosity, and the potential for new career paths, primarily symbolizing the emergence of a new way of life, a new social paradigm, and a world that is becoming increasingly tangible, especially in the field of fashion.

The emergence of the metaverse has garnered significant attention from the fashion industry, and many leading brands have already invested in metaverse innovation and commercialization.

Fashion brands have begun offering digital clothing collections by opening virtual stores on metaverse platforms. This contributes to the formation of a new economic and design space in the fashion sector. The metaverse offers various opportunities and possibilities for stakeholders, including technology developers, fashion brands, and consumers.

This new, virtual type of fashion show has been adopted by many brands, from the most famous brands such as Dolce & Gabbana and Tommy Hilfiger to less famous and emerging brands such as Auroboros (Piva, 2024).

The Metaverse offers fashion designers the opportunity to stage immersive and interactive virtual fashion shows. Replacing traditional physical runways, designers can create virtual catwalks in breathtaking digital environments. This innovation allows them to present their collections to a global audience without the constraints of physical spaces and logistical concerns. Virtual fashion shows open the door to limitless creativity and experimentation, enabling designers to push boundaries and create unique experiences that seamlessly blend fashion, technology, and artistic expression.

With the continued evolution of the Metaverse, the fashion industry can leverage the potential of the digital space to reshape fashion encounters, expand its reach to wider audiences, and delve into new creative horizons. This dynamic space serves as an exciting intersection of technology, art, and fashion, offering innovative ways for fashion brands to connect with consumers and influence the future of the industry (Mandal, 2023).

4. Virtual Clothing Design

The virtual clothing design process is a digital-based process that differs from traditional design approaches in the fashion industry. This process allows designers to create clothing prototypes in a digital environment, accelerating and facilitating processes from the design phase to production and marketing.

Virtual clothing design encompasses digital garments created using three-dimensional design software. These designs include features such as:

- Realistic fabric simulations
- Motion animations
- Avatar compatibility.

Virtual clothing allows users to express their digital identities without the need for a physical production process. The main advantages of virtual clothing design are:

- Reduced physical production costs
- Sustainable production possibilities
- Unlimited creative space for designers
- Development of digital identity and avatar fashion

Virtual clothing can be used by companies and designers to achieve the best fit values in the marketing and product development phases of real garments (Hernández et al., 2019: 250).

Virtual clothing design, representing a significant transformation for the fashion industry, plays a major role in terms of innovation, sustainability, and digitalization. This process adds a whole new dimension to traditional production and sales processes, and programs such as Browzwear, Optitex, Marvelous Designer, and CLO3D have been developed to create virtual clothing designs in the sector. While there are similarities between these programs, when examining the rankings of technology companies worldwide in the 3D modeling category, CLO3D ranks 6th in the top 20 list with a 3.11% market share and stands out as the only company on the list that creates models for the fashion industry. Furthermore; According to CLO Virtual Fashion Launches Global Community for Fashion Creators (2021), CLO3D is the most widely used program in the fashion industry to facilitate consumer purchasing or the projection and simulation of designer creations (Casciani et al., 2022; Liu and Liu, 2025; Naveen Kumar et al., 2025).

5. Conclusion

Digital fashion and the metaverse play a significant role in the future of fashion design. In addition, virtual clothing design offers different opportunities to the fashion industry in terms of both sustainability and new consumption models.

Digital technologies contributing to sustainability are used in the drawing, design, pattern making, production, and presentation stages. Realistic clothing, fabric, and print visuals created with computer-aided design and 3D modeling programs allow designers to make accurate decisions without needing physical samples and materials, conduct fittings digitally, and make as many trials as desired. Creating patterns and layout plans in computer programs reduces waste, increases efficiency, and minimizes the waste rate in the manufacturing process. The digitalization of garment fitting and photography processes in the conventional fashion system eliminates the need for production, while reducing material consumption and potential waste during the cutting stage to zero. In this context, it significantly contributes to the zero-waste strategy. Digitalization not only reduces resource consumption, but also reduces energy consumption and prevents environmental damage by organizing digital fashion shows instead of physical ones.

However, it is observed that there are also some challenges in the field of digital fashion, such as copyright, digital ownership, and technological infrastructure. The adaptation of fashion designers and brands to digital platforms is of great importance for the future of the sector. In this context, some suggestions that can be offered for the sector are listed below.

Suggestions:

- Increased use of digital design software in fashion design education
- Increasing the presence of fashion brands on metaverse platforms
- Developing academic studies on digital fashion design

In conclusion, digital fashion, metaverse, and virtual clothing applications are creating a new creative field in fashion design and playing an important role in the transformation of the sector.

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PAMUKTA ABİYOTİK STRES FAKTÖRLERİNE MELATONİNİN ETKİSİ

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ÖZET

Pamuk (*Gossypium hirsutum L.*), küresel tekstil endüstrisinin lif ihtiyacının yaklaşık %35'ini tek başına karşılayan ve dünya genelinde ekonomik kalkınma üzerinde hayati bir role sahip olan stratejik bir üründür. Ancak, pamuk endüstrisi zinciri günümüzde artan abiyotik stres faktörlerinin ciddi tehdidi altındadır. Abiyotik stresler arasında kuraklık, düşük ve yüksek sıcaklıklar, tuzluluk, radyasyon, ağır metaller ve kimyasal stresler pamuk üretiminde azalmalara yol açmaktadır. Bu abiyotik stres faktörlerinin yarattığı tahribatı hafifletmek amacıyla son yıllarda öne çıkan en önemli moleküllerden biri melatonindir. İlk kez 1995 yılında damarlı bitkilerde keşfedilen bu indolamin hormonu, oksin benzeri işlevler üstlenerek bitki büyüme ve gelişmesinde merkezi bir rol oynamaktadır. Melatonin; pamukta fotosentezi, iyon homeostazını ve antioksidan enzim aktivitelerini artırarak bitkinin biyotik ve abiyotik streslere karşı direncini stabilize etmektedir. Melatonin ayrıca çiçeklenme, kök ve sürgün büyümesi, meyve verme ve yaşlanma gibi stresten etkilenen gelişimsel süreçlerde de önemli rol oynar. Yapılan çalışmalar, ekzojen (dışarıdan) melatonin uygulamasının yapraklardaki nem durumunu iyileştirdiğini ve enzimatik antioksidan savunma sistemini güçlendirerek ve fizyolojik aktiviteleri teşvik ederek abiyotik stres kaynaklı verim kayıplarını etkili bir şekilde azalttığını kanıtlamıştır. Sonuç olarak melatonin, pamukta abiyotik stres toleransını artırmak, oksidatif hasarı onarmak ve sürdürülebilir tarımsal üretim potansiyelini korumak için kritik öneme sahip bir biyostimulant ve serbest radikal temizleyici olarak değerlendirilmektedir.

Anahtar Kelimler: Pamuk, melatonin, kuraklık, tuzluluk, ağır metal, abiyotik stres

THE EFFECT OF MELATONIN ON ABIOTIC STRESS FACTORS IN COTTON

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) is a strategic crop that alone meets approximately 35% of the global textile industry's fiber needs and plays a vital role in economic development worldwide. However, the cotton industry chain is currently under serious threat from increasing abiotic stress factors. Abiotic stresses such as drought, low and high temperatures, salinity, radiation, heavy metals, and chemical stresses lead to reductions in cotton production. In recent years, one of the most important molecules that has emerged to mitigate the damage caused by these abiotic stress factors is melatonin. This indolamine hormone, first discovered in vascular plants in 1995, plays a central role in plant growth and development by undertaking auxin-like functions. In cotton, melatonin stabilizes the plant's resistance to biotic and abiotic stresses by increasing photosynthesis, ionic homeostasis, and antioxidant enzyme activities. Melatonin also plays a significant role in stress-affected developmental processes such as flowering, root and shoot growth, fruiting, and senescence. Studies have shown that exogenous (external) melatonin application improves leaf moisture status and effectively reduces yield losses caused by abiotic stress by strengthening the enzymatic antioxidant defense system and stimulating physiological activities. Consequently, melatonin is considered a critical biostimulant and free radical scavenger for increasing abiotic stress tolerance, repairing oxidative damage, and preserving the potential for sustainable agricultural production in cotton.

Keywords: Cotton, melatonin, drought, salinity, heavy metal, abiotic stress

GİRİŞ

Pamuk (*Gossypium hirsutum L.),* küresel tekstil endüstrisinin lif ihtiyacının yaklaşık %35'ini tek başına karşılayan ve dünya genelinde ekonomik kalkınma üzerinde hayati bir role sahip olan stratejik bir üründür. Ancak, pamuk endüstrisi zinciri günümüzde artan abiyotik stres faktörlerinin ciddi tehdidi altındadır. Aşırı sıcaklık, kuraklık, tuzluluk vb. gibi abiyotik stresler, bitki büyümesini ve verimliliğini büyük ölçüde etkiler (Waqas vd., 2017; Vaughan vd., 2017; Zafar vd., 2018). Ekilebilir arazilerin yaklaşık %90'ının yukarıda belirtilen streslerden birine maruz kaldığı tahmin edilmektedir (Dos Reis vd., 2012). Dahası abiyotik stresler, küresel iklim değişikliğinin mevcut çağında ilerleyici bir gelişme göstermektedir ve dünya çapında tarımda sürdürülebilirliğe büyük bir tehdit oluşturmaktadır (Nadeem vd, 2018; Nadeem vd., 2019). İklim değişikliğinin yol açtığı abiyotik streslerin neden olduğu ürün kayıplarını en aza indirmek için etkili stratejiler geliştirmek gereklidir. Abiyotik stresler arasında kuraklık, düşük ve yüksek sıcaklıklar, tuzluluk, radyasyon, ağır metaller ve kimyasal stresler pamuk üretiminde azalmalara yol açmaktadır. Bu abiyotik stres faktörlerinin yarattığı tahribatı hafifletmek amacıyla son yıllarda öne çıkan en önemli moleküllerden biri melatonindir. Biyoaktif bir molekül olan melatonin (N-asetil-5-metoksitriptamin), organizmalarda yaygın olarak bulunur ve ilk olarak ineklerin epifiz bezinde keşfedilmesinden bu yana kapsamlı bir şekilde incelenmiştir (Lerner vd., 1958). Önceki çalışmalar, melatoninin insan sirkadiyen ritminin, uykunun, ruh halinin, vücut sıcaklığının, iştahın ve immünolojik yanıtların korunması için gerekli olduğunu göstermiştir (Socaciu vd., 2020). Ayrıca, antioksidan, anti inflamatuar ve diğer biyolojik fonksiyonların da melatonin tarafından düzenlendiği kanıtlanmıştır; bu nedenle melatonin, hastalık patogenezi ve ilaç geliştirme alanlarında yaygın olarak kullanılmaktadır (Millet-Boureima vd., 2021). İlk kez 1995 yılında damarlı bitkilerde keşfedilen bu indolamin hormonu, oksin benzeri işlevler üstlenerek bitki büyüme ve gelişmesinde merkezi bir rol oynamaktadır. Melatonin; pamukta fotosentezi, iyon homeostazını ve antioksidan enzim aktivitelerini artırarak bitkilerin biyotik ve abiyotik streslere karşı direncini stabilize etmektedir.

Melatoninin Kuraklık Stresi Üzerine Etkisi

Kuraklık stresi, küresel ürün kayıplarının başlıca nedenidir, çünkü ekilebilir alanlarda tarımsal üretimi üçte birden fazla sınırlandırır (Dai, 2013; Lesk vd., 2016), bu da dünya çapındaki ürün verimi ve üretkenliğinin yaklaşık %70'lik kaybına neden olur (Seleiman vd., 2020). Üstelik, su kaynaklarının dağılımı dengesizleştikçe, su kıtlığı arttıkça ve küresel ısınma nedeniyle iklim gelecekte değiştikçe kuraklık stresinin daha yoğun ve sık olacağı tahmin edilmektedir (Dai, 2013; Lesk vd., 2016; Chen vd., 2022). Pamuk (*Gossypium hirsutum* L.), küresel ölçekte en yaygın olarak yetiştirilen lif bitkisi olması nedeniyle ekonomik açıdan en önemli nakit ürünlerden biridir. Dünya pamuk yetiştirme alanlarının yaklaşık %70'i kuraklıktan etkilenmektedir (Wu vd., 2022), bu da pamuk veriminde ve kalitesinde önemli bir azalışa neden olmaktadır (Ullah vd., 2017). Bu azalma, pamuk üretiminin güvenliğini ciddi şekilde tehdit etmektedir. Bu nedenle, pamuğun kuraklığa dayanıklılığının çevre dostu bir şekilde iyileştirilmesi, pamuk üretimine önemli ölçüde fayda sağlayacaktır. Bitki büyüme düzenleyicilerinin dışarıdan uygulanmasının, kuraklık stresinin ürünler üzerindeki olumsuz etkilerini birden fazla şekilde hafiflettiği kanıtlanmıştır (Guo vd., 2023). Melatonin (N-asetil-5-metoksitriptamin), bitkilerde yaygın olarak bulunan ve bitkilerin çeşitli biyotik ve abiyotik streslere karşı direncini artırmak için bitki büyüme düzenleyicisi olarak bilinen doğal olarak oluşan bir indoldür (Sun vd., 2021; Wang vd., 2022). Son yıllarda melatonin, serbest radikalleri temizleme konusundaki güçlü yeteneği sayesinde kuraklık stresinin hafifletilmesinde umut vaat etmektedir (Wang vd., 2022). Hu vd. (2022) yakın zamanda melatonin uygulamasının pamuk verimini %38,3-60,6 oranında artırdığını bildirmiştir. Pamuk, abiyotik streslere karşı belirli bir toleransa sahip olsa da, verim potansiyeli ve lif kalitesi kuraklık, yüksek sıcaklık ve su baskını

gibi olumsuz koşullar altında önemli ölçüde kısıtlanabilir (Gao vd. 2021; Ullah vd. 2017). Özellikle, pamuk üretiminde önemli bir sınırlayıcı faktör olan kuraklık stresi, normal fizyolojik fonksiyonları birden fazla yolla bozar: bitkinin iç su dengesini bozarken aynı zamanda reaktif oksijen türlerinin aşırı birikmesine ve ardından oksidatif hasara yol açarak pamuk büyümesini ve gelişimini sistematik olarak engeller (Yu vd. 2023). Küresel pamuk üretiminin yaklaşık %73'ünün sulamaya bağımlı olması, ürünü kuraklık riskine karşı son derece hassas kılmaktadır. Kuraklık stresi; bitkinin iç su dengesini bozarak, reaktif oksijen türlerinin (ROS) aşırı birikmesine ve buna bağlı sistemik oksidatif hasara yol açarak lif veriminde %34'e varan kayıplar oluşturmaktadır. Bitkiler için suyu yakalayan ana organ olan kök sistemi, optimal mimari ve fizyolojik duruma sahip olması sayesinde çevreden su emilimini garanti eder (Hund vd. 2009; Kuromori vd. 2018; Dinneny 2019), bu da kuraklığa dayanıklılık için kritik öneme sahiptir. Kuraklık stresi, kök büyümesi ve gelişimi üzerinde önemli etkilere sahiptir (Gilbert ve Medina 2016; Chen vd. 2022). Melatonin uygulaması pamukta kök uzamasını teşvik edebilir ve yanal kök sayısını artırarak toplam kök yüzey alanını ve toplam kök hacmini genişletebilir, bu da bitki büyümesini destekleyen daha zengin bir kök sistemiyle sonuçlanır (Zhu vd., 2023). Melatonin ayrıca ozmotik düzenlemeyi, solunum enzim aktivitesini artırmakta, su ve temel besin maddeleri için spesifik kök uzunluğu alım oranlarını iyileştirmektedir. Dahası, melatoninin pamukta kök uzunluğu, bitki yüksekliği, gövde çapı ve yaprak alanındaki artışlarla kanıtlandığı gibi kök ve toprak üstü büyümesini teşvik ettiği tespit edilmiştir. Eksojen melatonin uygulamasının, kuraklık stresinin bitkiler üzerindeki olumsuz etkilerini hafiflettiği ve kök sistem0inin anatomik yapısını etkilediği belirtilmiştir (Zhang vd., 2025). Chen vd., 2018, kuraklığın pamuk köklerinin biyokütlesini azalttığını bulmuştur. Bu nedenle, kuraklık stresi altında bitkinin yeterli su temini için kök büyümesinin korunması veya teşvik edilmesi çok önemlidir. Melatonin, çok işlevli bir biyomolekül olup, kuraklık da dahil olmak üzere olumsuz çevresel koşullar altında kök gelişimini destekler ve ürün verimliliğini artırır (Madebo vd. 2021; Xu vd. 2023; He vd. 2023). Örneğin, Yang ve vd., (2023), dışarıdan verilen melatoninin, antioksidan enzim sistemini güçlendirerek kuraklık stresi altındaki pamukta yaprak yaşlanmasını etkili bir şekilde geciktirdiğini bildirmiştir. Ayrıca, dışarıdan uygulanan melatonin, yaprak nem durumunu iyileştirerek ve enzimatik antioksidan sistemi destekleyerek kuraklığın neden olduğu pamukta verim kayıplarını etkili bir şekilde azaltabilir (Hu vd., 2021, 2022). Ayrıca, dışarıdan uygulanan melatonin, yapraktaki nem durumunu iyileştirerek ve enzimatik antioksidan sistemi destekleyerek pamukta kuraklığın neden olduğu verim kayıplarını etkili bir şekilde azaltabilir (Hu vd., 2021, 2022).

Melatoninin Tuz Stresi Üzerine Etkisi

Abiyotik stres faktörü olan tuzluluk, tarımsal üretimi azaltan ve önemli gelir kayıplarına yol açan dünya çapında bir endişe kaynağıdır. Dünya genelinde ekilebilir arazilerin %50'sinden fazlasının 2050 yılına kadar tuzluluktan etkileneceği öngörülmektedir (Demiral ve Türkan 2006; Saeed vd. 2021). Toprak tuzlanması, dünya tarımının karşı karşıya olduğu en büyük zorluklardan biridir (Zhu, 2001), çünkü tuzlanma bitkilerin büyüme ve gelişmesini engeller ve ürün verimini düşürür (Shahzad vd., 2021). Yapılan çalışmalara göre, aşırı tuz konsantrasyonları bitki morfolojik ve fizyolojik sistemlerini bozar ve gelişmeyi durdurur (Cirillo vd., 2016). Tuzluluk, ROS sentezini artırır ve hücre zarlarına ciddi şekilde zarar veren oksidatif stresi teşvik eder (Arora vd., 2008). Bu nedenle, tuzlanmış tarım arazilerinin verimini artırmak için pamuğun tuz toleransının iyileştirilmesi gerekmektedir ve pamuğun tuz toleransının incelenmesi giderek daha önemli hale gelmektedir. Tuz hasarı, pamuk fidelerinin büyümesini ve verim oluşumunu sınırlayan önemli bir faktördür (Munns & Tester, 2008). Tuz stresi, bitkilerde iyon homeostazını bozabilir, iyon zehirlenmesine neden olabilir, hücrelerin su ve ozmotik potansiyellerini azaltabilir ve ozmotik strese yol açabilir (Abbasi vd., 2016). Bitkiler

tuz stresine maruz kaldığında, en yaygın ana olgu büyüme inhibisyonudur (Towfique, Hafiz & Sen, 2013). Fide aşaması, pamuğun büyüme ve gelişmesinde hassas ve kritik bir aşamadır ve tuz stresi tarafından ciddi şekilde etkilenir; bu nedenle tuz stresi altında pamuk fidelerinin büyüme ve düzenlenmesinin araştırılması büyük önem taşımaktadır. Tuz stresinin, pamuk fidelerinin kök hücre yapısına zarar verdiği ve fizyolojik sistemini bozduğu tespit edilmiş, melatonin uygulanan tohumlar tuz stresine maruz bırakıldıktan sonra, pamuk fidelerinin köklerindeki SOD, CAT ve POD aktivitelerinin sırasıyla %10-25, %50-60 ve %50-60 oranında arttığı belirtilmiştir (Duan vd., 2022).

Tuz stresi, bitkilere iyonik stres, ozmotik stres ve oksidatif stres gibi ikincil stresler getirerek bitkilerin normal gelişimini engeller. Bitkiler tuz stresine maruz kaldığında, fizyolojik ve biyokimyasal reaksiyonları normal şekilde ilerleyemez, bu da verim ve kalitenin azalmasına ve hatta bitki ölümüne yol açar (Parida & Das, 2005; Liang vd., 2018). Dışarıdan uygulanan Melatonin, K+ alımını teşvik ederek tuz stresinin etkilerini tersine çevirir; bu da melatoninin, stresin neden olduğu zararı azaltarak iyon homeostazını yönetebileceği anlamına gelir. Tuz stresine maruz kalan bitkiler, iyon dengesizliğine ve hücresel toksisiteye neden olan Na+ biriktirir. Ancak K+ konsantrasyonu azaldıkça, tuz stresini0n bu etkisi tersine döner (Zhan vd., 2019). Melatonin'in dışarıdan verilmesi veya melatonin üretim enzimlerinin genetik olarak değiştirilmesi, melatonin'in tuz stresi direncindeki faydalı etkilerinin kademeli olarak geliştirilmesinde kullanılmıştır (Kanwar vd., 2018). Pamuk, dünyanın en uzun ekim endüstri zincirine sahip tarla bitkisidir ve ulusal ekonomilerde önemli bir rol oynamaktadır (Luo vd., 2018). Fide aşaması, pamuğun büyüme ve gelişmesinde hassas ve kritik bir aşamadır ve tuz stresi tarafından ciddi şekilde etkilenir; bu nedenle tuz stresi altında pamuk fidelerinin büyüme ve düzenlenmesinin araştırılması büyük önem taşımaktadır.

Melatoninin Düşük Sıcaklık Stresi Üzerine Etkisi

Abiyotik stres faktörleri arasında, düşük sıcaklık stresi bitki büyümesini, gelişimini ve verimini önemli ölçüde engeller. Düşük sıcaklık stresi, 0 ila 15 °C arasındaki soğuklama ve 0 °C'nin altındaki donma olarak ikiye ayrılabilir (Zhang ve Zhou 2023) Pamukta vejetatif büyüme sırasında, soğuk stresi morfo-fizyolojik özellikleri olumsuz etkiler. Morfolojik düzeyde, sıcaklık dalgalanması kök büyümesi üzerinde önemli bir etkiye sahiptir (Zhou vd.,2021). Ayrıca, fizyolojik düzeyde, prolin, protein ve çözünür şekerlerin birikimi, sürgün ve köklerdeki hücreleri düşük sıcaklık hasarına karşı korur (Theocharis vd. 2012). Dahası, soğuk stresi net fotosentez aktivitesini azaltarak pamuk büyümesini ve verimini azaltır (Snider vd. 2022). Bitkiler, soğuk stresinin zararlı etkilerini hafifletmek için hücre zarı stabilitesini ve protein yapısını korurken antioksidan aktiviteyi de artırır (Hao vd., 2018).

Düşük sıcaklık stresi bitki büyümesini ve verimliliğini olumsuz etkiler ve bu da dünya genelinde ürün kaybına neden olur (Zhang vd., 2013). Fotosentez, soğuk stresinden etkilenen birincil süreçtir. Soğuk stresi fotosentetik kapasiteyi azaltır, kloroplast gelişimini etkiler ve klorofil floresansında düşüşe neden olur (Han vd., 2017; Farooq vd., 2019; Adam vd., 2021)

Optimal aralığın altındaki sıcaklıklar bitki gelişimini ve verimini olumsuz etkiler. Düşük sıcaklıklar, sıcak iklim bitkisinin metabolizmasının birçok yönünü etkiler; bunlar arasında şekerler, fenolikler, fosfolipidler, protein ve ATP bulunur ve hatta su stresi ve hücre zarlarında hasara neden olabilir (Decoteau, 2000; Kratsch ve Wise, 2000). Düşük sıcaklıklar, bitki hücrelerinin daha fazla ROS üretmesine neden olur; bu da lipid peroksidasyonuna ve protein bozulmasına yol açabilir (Fan vd., 2014). Yapılan bir araştırmaya göre, soğuk stresine maruz kaldığında, melatonin takviyesi gen ekspresyonunu artırmış ve melatonin üretimini uyarmıştır (Bajwa vd., 2014). Fitomelatonin, soğuk stresi altında morfo-fizyolojik ve moleküler

aktivitelerini iyileştirerek ürünün büyümesini ve verimini artırır. Melatoninin yapraktan uygulanması çeşitli fizyolojik süreçleri etkileyerek bitkinin soğuk stresine karşı direncini artırır (Ahmad vd. 2023). Son çalışmalar, melatoninin (MT) soğuk stresi altındaki bitkilere verilen zararı hafifletebileceğini, büyüme ve gelişmeyi teşvik edebileceğini, 100 μM MT ön uygulamasının pamuğun soğuk direncini en önemli ölçüde iyileştirdiğini göstermiştir. Ayrıca, soğuk stresi altındaki pamuğun solma durumu, fotosentetik oranı, stoma iletkenliği, maksimum fotokimyasal verimliliği ve fotosentetik performans indeksi sırasıyla %116,92, %47,16, %32,30 ve %50,22 oranında artmıştır (Zhu vd., 2024). Melatonin uygulamasının düşük sıcaklık stresi üzerinde etkisi üzerine yürütülen araştırmaların sınırlı olduğu ve bu konuda daha fazla araştırmalara ihtiyaç duyulduğu düşünülmektedir.

Melatoninin Yüksek Sıcaklık Stresi Üzerine Etkisi

Küresel iklim değişikliği pek çok değişikliklere neden olmuştur, ancak bunlardan en belirgin olanı sıcaklık değişimidir. Sık görülen sıcak hava dalgaları pamuk bitkisi üzerinde derin bir etkiye sahiptir. Bir bitkinin gelişiminin her aşaması ideal bir sıcaklık gerektirir; bu sıcaklık türe ve hatta çeşide göre değişir. Optimum sıcaklık aralığının üstündeki sıcaklıklar ısı stresine neden olmaktadır.

Sıcaklık, tohumun çimlenmesinden hasada kadar bitki büyümesini ve işlevlerini etkiler. Bir ürün için optimum sıcaklık aralığı, ürünün en iyi performansı gösterdiği aralıktır. Sıcaklıktaki her iki aşırı uç da su ve besin alım kapasitesini sınırlar, bu da çiçeklenmeyi, meyve oluşumunu ve tohum oluşumunu etkiler (Pierce, 1987). Sıcaklık stresi, karbonhidrat metabolizmasını, hormon sinyallerini, kalsiyum ve gen düzenlemesini ve ekspresyonunu etkileyerek temel fizyolojik ve biyokimyasal süreçleri bozar (Luqman vd., 2025). Aşırı sıcaklık stresinde hücresel hasar veya hücre ölümü dakikalar içinde meydana gelebilir ve bu da hücresel organizasyonun çökmesine yol açabilir. Sıcaklık stresi, çimlenme, büyüme, gelişme, üreme ve verim gibi bitki süreçlerinin tüm yönlerini etkiler (Hasanuzzaman vd., 2013). Yüksek sıcaklıkların besin alınımını olumsuz etkilemesi, membran bütünlüğünü azaltması ve su stresi altındaki yapraklarda görülenlere benzer nekrotik lekeler oluşturması gibi, yüksek sıcaklıklar da birçok bitki türünün erken ölümüne neden olabilir (Hall, 2018).

Isı stresi bitkileri fizyolojik (örneğin, fotosentez, hücre zarı termostabilitesi ve oksidatif hasar), transkripsiyonel, transkripsiyon sonrası (örneğin, kodlayıcı olmayan RNA'lar) ve epigenetik (örneğin, DNA metilasyonu, histon modifikasyonu ve kromatin yeniden şekillendirme) seviyelerde etkiler (Zhao vd., 2020). Aşırı sıcaklıklar, tohumun çimlenmesini ve fide çıkışını engeller, besin ve su alımını kısıtlar, çiçeklenmeyi, tohum ve meyve gelişimini olumsuz etkiler ve sonuç olarak bitkilerin ölümüne yol açar. Eksojen melatonin uygulamalarının bitkileri sıcaklık dalgalanmalarından korumaya yardımcı olduğu bildirilmiştir (Tan vd., 2000). Isı stresi sırasında, endojen melatonin seviyeleri artar ve böylece bitkinin termotoleransı iyileşir. Isı stresi altında, dışarıdan uygulanan melatonin uygulaması, ROS birikiminin kontrolü ve prolin metabolizmasının artırılması yoluyla bitki antioksidan savunma sistemlerini güçlendirebilir.

Melatoninin Ağır Metaller Üzerine Etkisi

Toprak, insan yaşamı için en önemli kaynaklardan biridir. Son yıllarda, kentleşme, sanayi ve tarımın hızlı gelişmesi ve mineral kaynaklarının büyük ölçekli geliştirilmesi ve kullanımıyla birlikte, toprakta ağır metal kirliliği giderek daha ciddi hale gelmiştir. Çünkü kirleticiler çevrede birikmeye devam etmektedir. Ağır metallerle kirlenmiş toprak alanı, çevredeki ağır metallerin sürekli göçü, birikimi ve dönüşümüyle birlikte artmıştır. Ağır metaller bitkiler için zehirlidir. Ağır metal stresi, ROS birikimini tetikleyerek ve kloroplastlara zarar vererek kök büyümesini

baskılayabilir ve yaprak yaşlanmasını hızlandırabilir. Ayrıca, Calvin döngüsü enzimleri, fotosentez ve karbonhidrat metabolizması da ağır metal toksisitesi tarafından engellenir (Hasan vd., 2015, 2019; Ni vd., 2018). Kurşun (Pb), bakır, vanadyum ve alüminyumun neden olduğu toksisite, redoks homeostazını bozabilir ve redoks ajanlarının birikimini hızlandırabilir (Nagajyoti vd., 2010). Araştırmalar melatoninin, ağır metal kaynaklı kök büyüme ve aktivite baskılanmasını hafifletebileceğini göstermektedir (Ni vd., 2018; Jahan vd., 2020). Endojen melatonin üretimi, ağır metal toleransını güçlendirmek için eksojen melatonin uygulaması ile uyarılabilir. Eksojen melatonin ayrıca bitkilerin antioksidan potansiyelini artırır ve alüminyum stresi altında lipid peroksidasyonunu azaltır (Sun vd., 2020). Melatonin, gaz değişimini iyileştirirken fotosentetik pigmentlerin, minerallerin, besin maddelerinin ve ikincil metabolitlerin içeriğini artırarak nikel fitotoksisitesini hafifletir (Jahan vd., 2020). NO, ağır metal stresi altındaki bitkilerde redoks homeostazının yeniden kurulmasında hayati bir role sahiptir. Melatonin ve NO arasındaki etkileşim, Pb ve Cd stres toleransını artırır (Kaya vd., 2019; Okant ve Kaya, 2019). Antioksidan seviyelerini düzenlemenin yanı sıra, melatonin ağır metal alımını ve tutulmasını artırarak ağır metal toleransına aracılık eder. Cd, vanadyum ve bakır, eksojen melatonin uygulamasından sonra bitki hücrelerinden uzaklaştırılır veya tutulur (Nawaz vd., 2018; Cao vd., 2019; Hasan vd., 2019).

Eksojen melatonin uygulaması ile Cd stresi altında bulunan pamuk bitkisinin fotosentetik oranını ve klorofil seviyesini artırdığı ve pamuğun büyüme performansının iyileştirilmesine etkili bir şekilde katkıda bulunduğu bildirilmiştir (Sami vd., 2020). Yu vd.. 2024, MT'nin dışarıdan uygulanmasının, Cd uygulamasına kıyasla toprak üstü biyokütleyi %28,56 oranında arttırdığı belirtilmiştir. Sonuç olarak, MT, Cd stresi altında fotosentez ürünlerinin birikimini artırarak pamuk bitkisinin toprak üstü biyokütle birikimini artırabilme potansiyeline sahiptir.

Azot, bitki büyümesi ve gelişimi için gerekli bir makro besin maddesidir ve azot eksikliği durumunda bitki büyümesi engellenebilir. Çalışmalar, NO3-'ün bitkilerde yanal köklerin uzamasını uyarabileceğini ve dışarıdan verilen melatoninin bitkilerde NO3- alımını artırarak bitki köklerinin gelişimini destekleyebileceğini ve N elementlerinin bitki kökleri tarafından emilimini kolaylaştırabileceğini göstermiştir. Melatonin bitki kök gelişimini destekleyerek ve oksidatif hasarı azaltarak bitkinin strese karşı toleransını artırabilir (Hu vd., 2020). Melatonin, bitkilerde ağır metal iyonlarının toksik etkilerini azaltır; bu etki muhtemelen bitkilerde küçük moleküllü şelatlayıcı maddelerin sentezini artırarak ağır metal iyonlarının göçünü engeller veya bitkilerdeki iyon dengesini ve redoks durumunu düzenler. Bitki gelişimi ve veriminin ağır metal kirliliğinden etkilenmesi ciddi bir çevre sorunudur. Bitki büyümesinde azalma, üretim ve kalite bunun sonucudur. Genel olarak, metaller bir bitkinin varlığı için gereklidir; ancak, alüminyum (Al), kadmiyum (Cd), krom (Cr), çinko (Zn), bakır (Cu), kurşun (Pb) ve nikel (Ni) gibi bazı metaller, kök bölgesinde bulunduklarında tehlikeli etkilere sahiptir (Prasad ve Strazalka, 2002). Bu ağır metaller, bitkilerde klorofil seviyelerini ve fotosentez oranlarını düşüren, etilen seviyelerini yükselten, kök ve sürgün gelişimini yavaşlatan, CO_2 fiksasyonunu azaltan ve şeker transferini kısıtlayan ROS sentezini teşvik eder; bunların tümü oksidatif hasara neden olur (Buchanan vd., 2000).

Sonuç Ve Öneriler

Abiyotik stresler, bitkilerde fizyolojik ve moleküler düzeyde çeşitli bozulmalara yol açarak küresel ölçekte verim kayıplarına neden olmaktadır. Melatonin, birçok damarlı bitkide bulunan ve stres koşullarında önemli rol oynayan biyoaktif bir moleküldür. Araştırmalar, eksojen olarak uygulanan melatoninin çeşitli stres koşullarında bitki büyümesini ve canlılığını yeniden desteklediğini ve bitki gövdelerinin ve yapraklarının yaşlanmasını yavaşlatabildiğini ortaya koymaktadır. Melatoninin bu etkisi, büyük ölçüde antioksidan metabolizmayı düzenlemesi ve

fotosentetik sistemi korumasıyla ilişkilendirilmektedir. Fotosentez kapasitesindeki artış, ürün verimliliğini yükselterek küresel gıda güvencesine katkı sağlayabilecek önemli bir faktördür. Abiyotik streslerin ürün kalitesi ve verimi üzerindeki olumsuz etkileri göz önüne alındığında, melatoninin tarla koşullarında uygulanması tarımsal açıdan umut verici bir yaklaşım olarak değerlendirilmektedir. Bununla birlikte, melatoninin stres koşullarında bitkilerde oluşturduğu iyileştirici etkilerin altında yatan genetik ve metabolik mekanizmaların daha ayrıntılı olarak incelenmesine ihtiyaç vardır. Özellikle fitohormon mutantları kullanılarak yapılacak çalışmalar, melatoninin diğer hormonlarla etkileşimini ve farklı sinyal yollarındaki rolünü daha iyi açıklayabilir. Ayrıca melatoninin sadece verimi artırmakla kalmayıp ürünlerin besin değerini de iyileştirdiği gösterilmiştir. Melatonin bakımından zengin bitkilerin, kirlenmiş toprakların iyileştirilmesi ve fitoremediasyon uygulamalarında kullanımı da önemli bir potansiyel taşımaktadır. Gelecekte, abiyotik stres altında melatonine verilen yanıtları düzenleyen fizyolojik, biyokimyasal ve anatomik süreçlerin anlaşılması için omik teknolojilere dayalı kapsamlı moleküler çalışmaların yapılması büyük önem arz etmektedir.

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IMPACT OF GLOBAL EVENT ON STOCK MARKET VOLATİLİTY: A COMPARATİVE STUDY OF PRE-, DURİNG- AND POST-EVENT PERFORMANCE

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ABSTRACT

Global events such as pandemics, geopolitical conflicts, and financial crises significantly influence stock market behaviour by increasing uncertainty and investor risk perception. This study examines the impact of a major global event on stock market volatility by comparing market performance during pre-event, during-event, and post-event periods. Using an event study framework and assumed data for a benchmark stock index, the study analyses changes in returns and volatility across the three phases. Descriptive statistics and comparative analysis are employed to assess volatility patterns and return behaviour. The findings indicate that market volatility increases sharply during the event period, accompanied by negative average returns, while the post-event phase shows gradual stabilization and recovery. The study highlights the sensitivity of financial markets to global shocks and provides insights useful for investors, portfolio managers, and policymakers in managing risk during periods of extreme uncertainty.

Keywords: Global Events, Stock Market Volatility, Event Study, Market Performance, Financial Uncertainty

Introduction

Financial markets operate in an environment characterized by uncertainty, where information flow and investor sentiment play a crucial role in price formation. Global events such as wars, pandemics, financial crises, and major geopolitical developments act as powerful external shocks that disrupt normal market functioning. These events increase uncertainty, alter investor expectations, and often trigger sharp fluctuations in stock prices and volatility. Understanding how stock markets respond before, during, and after such events is essential for investors, regulators, and policymakers.

Stock market volatility is widely regarded as a measure of risk and uncertainty. During periods of global turmoil, investors tend to react emotionally, leading to panic selling, herd behaviour, and excessive market movements. The Efficient Market Hypothesis suggests that markets quickly incorporate new information into prices; however, during extraordinary global events, information asymmetry and behavioural biases may cause deviations from rational pricing. As a result, volatility tends to rise significantly during such periods.

Comparative analysis of market performance across pre-event, during-event, and post-event periods provides valuable insights into the resilience and adaptive capacity of financial markets. The pre-event period reflects normal market conditions, the during-event phase captures the immediate reaction to uncertainty, and the post-event period indicates the speed and extent of market recovery. Such analysis helps investors understand risk dynamics and design appropriate portfolio strategies.

In the Indian context, stock markets have experienced heightened volatility during events such as the global financial crisis, COVID-19 pandemic, and geopolitical tensions. Studying volatility patterns across different phases of a global event contributes to better risk assessment and policy formulation. This study attempts to analyze stock market volatility using an event study approach to understand the magnitude and persistence of global event impacts.

Review of Literature

The relationship between global events and stock market volatility has been widely studied in financial literature. Fama (1991) emphasized that financial markets respond rapidly to new and unexpected information, leading to price adjustments and changes in volatility. Global events represent significant information shocks that affect investor expectations and market behaviour.

Baker, Bloom, Davis, and Terry (2020) documented unprecedented levels of stock market volatility during global crises, attributing these fluctuations to heightened economic uncertainty and policy responses. Bekaert, Hoerova, and Lo Duca (2013) examined global volatility spillovers and found that uncertainty originating in one market can quickly spread to others, especially during crisis periods.

Studies focusing on emerging markets suggest that global events have a stronger impact due to higher exposure to international capital flows. Kumar and Dhankar (2017) found that Indian stock markets experience sharp volatility spikes during global crises, followed by gradual stabilization. Event study methodologies have been widely used to analyze market reactions, highlighting abnormal returns and increased volatility during event windows.

Research Methodology

Objectives of Study:

•To examine the behaviour of stock market returns and volatility during the pre-event period.

•To analyse the impact of a global event on stock market volatility during the event period.

Analysis

Descriptive Statistics

Period	Average Return (%)	Volatility (%)
Pre-event	2.4	13.1
During-event	-6.8	39.6
Post-event	3.2	20.4

The pre-event period exhibits moderate returns and relatively low volatility, indicating stable market conditions. During the event period, average returns turn negative, and volatility increases sharply, reflecting heightened uncertainty. In the post-event period, volatility declines but remains higher than pre-event levels, suggesting gradual market normalization.

Discussion

The analysis clearly demonstrates that global events have a significant impact on stock market volatility. The sharp increase in volatility during the event period indicates elevated risk perception and uncertainty among investors. Negative returns during this phase suggest panic-driven selling and risk aversion. These findings are consistent with behavioral finance theories, which argue that investors tend to overreact to negative information during crisis periods.

The post-event phase shows a decline in volatility and a recovery in returns, indicating that markets gradually absorb information and adjust to new conditions. However, volatility does not immediately return to pre-event levels, suggesting lingering uncertainty. This highlights the importance of effective risk management strategies, such as diversification and hedging, during periods of global uncertainty.

Conclusion

The study concludes that global events significantly influence stock market volatility and returns. Market volatility increases sharply during the event period, reflecting heightened uncertainty and investor fear, while the post-event phase shows gradual stabilization and recovery. The findings emphasize that financial markets are highly sensitive to global shocks, especially in emerging economies.

For investors and portfolio managers, understanding volatility patterns across different event phases is crucial for effective risk management and investment decision-making. Policymakers can use such insights to implement timely measures to stabilize markets during crises. Future research may extend this study by using real market data, applying advanced volatility models, and comparing multiple global events to enhance empirical robustness.

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EFFECTS OF DIATOMITE AND SOIL MOISTURE REGIME ON IONIC BALANCE AND SOIL CHEMICAL PROPERTIES IN A CALCAREOUS–SLIGHTLY ALKALINE SOIL

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Abstract

The effects of diatomite application and soil moisture regime on soil chemical properties, exchangeable cations, and soil solution ionic composition were evaluated under greenhouse conditions in a calcareous– slightly alkaline soil. The experiment was conducted as a pot study based on a completely randomized design with three replications, including three diatomite doses (0%, 15%, and 30% v/v) and three soil moisture regimes corresponding to 100%, 60%, and 40% of field capacity (FC100, FC60, and FC40, respectively). The results showed that diatomite application and soil moisture regime significantly influenced soil chemical behavior in a parameter-dependent manner. Electrical conductivity (EC) and total soluble salts increased with increasing diatomite dose, particularly under FC60, indicating enhanced accumulation of soluble ions. In contrast, exchangeable Na, water-soluble Na, and sodium adsorption ratio (SAR) decreased markedly with diatomite application, whereas exchangeable Ca and water-soluble Ca and Mg increased. These findings indicate that diatomite increased total ionic concentration while simultaneously shifting the soil system toward a more favorable Ca–Mg-dominated ionic balance. The response of available nutrients was more variable. Available P_2O_5 was significantly affected by soil moisture regime and the diatomite × soil moisture regime interaction, with the highest values observed under moderate water deficit conditions. In contrast, available K_2O generally decreased with increasing diatomite dose, suggesting redistribution among soil fractions rather than net depletion. The contrasting trends observed between exchangeable and water-soluble forms of Ca and Mg further suggest that diatomite acted primarily through ion redistribution and modification of soil chemical equilibria rather than through simple nutrient enrichment. Among the tested soil moisture regimes, FC60 produced the most pronounced responses, indicating that moderate water deficit enhanced the expression of diatomite effects by limiting leaching and promoting ion concentration and redistribution processes. Overall, the findings demonstrate that diatomite functions as a mineral amendment capable of improving sodicity-related chemical conditions by reducing Na dominance and enhancing Ca–Mg balance, despite increasing total salinity levels. These results highlight that the effectiveness of diatomite is strongly dependent on soil moisture regime and should therefore be evaluated in conjunction with water management conditions. Diatomite shows potential as a soil amendment for improving ionic balance in calcareous–slightly alkaline soils; however, its practical suitability should be assessed carefully under field conditions, particularly in relation to crop response, salinity risk, and long-term soil behavior.

Keywords: Diatomite, soil moisture regime, calcareous–slightly alkaline soil, ionic balance, salinity and sodicity, exchangeable cations, soil solution

KİREÇLİ–HAFİF ALKALİ BİR TOPRAKTA DİYATOMİT VE TOPRAK NEM REJİMİNİN İYONİK DENGE VE TOPRAK KİMYASAL ÖZELLİKLERİ ÜZERİNE ETKİLERİ

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Özet

Kireçli–hafif alkali bir toprakta, diyatomit uygulaması ve toprak nem rejiminin toprak kimyasal özellikleri, değişebilir katyonlar ve toprak çözeltisinin iyonik bileşimi üzerindeki etkileri sera koşullarında değerlendirilmiştir. Deneme, üç farklı diyatomit dozu (%0, %15 ve %30) ile tarla kapasitesinin %100, %60 ve %40 seviyelerini temsil eden üç ayrı toprak nem rejimini (sırasıyla TK100, TK60 ve TK40) kapsayacak şekilde, üç tekerrürlü tesadüf parselleri deneme desenine göre saksı koşullarında gerçekleştirilmiştir. Sonuçlar, diyatomit uygulaması ve toprak nem rejiminin, incelenen parametreye bağlı olarak toprak kimyasal davranışını önemli ölçüde etkilediğini göstermiştir. Elektriksel iletkenlik (EC) ve toplam çözünür tuzlar, özellikle TK60 koşulunda, artan diyatomit dozu ile birlikte yükselmiş; bu durum çözünür iyonların birikiminin arttığını göstermiştir. Buna karşılık, değişebilir Na, suda çözünebilir Na ve sodyum adsorpsiyon oranı (SAR) diyatomit uygulamasıyla belirgin şekilde azalmış; buna karşın değişebilir Ca ile suda çözünebilir Ca ve Mg artmıştır. Bu bulgular, diyatomitin toplam iyon konsantrasyonunu artırırken aynı zamanda toprak sistemini daha uygun bir Ca–Mg baskın iyonik dengeye yönlendirdiğini göstermektedir. Yarayışlı besin elementlerinin etkisi ise daha değişken olmuştur. Yarayışlı P_2O_5, toprak nem rejimi ve diyatomit × toprak nem rejimi etkileşiminden önemli ölçüde etkilenmiş; en yüksek değerler orta düzey su kısıtı koşullarında (TK60) gözlenmiştir. Buna karşılık, yarayışlı K_2O genellikle artan diyatomit dozu ile azalmış; bu durum net bir azalmadan ziyade toprak fraksiyonları arasında yeniden dağılıma işaret etmektedir. Ca ve Mg'nin değişebilir ve suda çözünebilir formları arasındaki zıt eğilimler, diyatomitin basit bir besin zenginleştirmesinden çok, iyonların yeniden dağılımı ve toprak kimyasal dengelerinin değiştirilmesi yoluyla etkili olduğunu göstermektedir. Toprak nem rejimleri arasında TK60 en belirgin tepkileri oluşturmuş; bu durum orta düzey su kısıtının yıkanmayı sınırlayarak ve iyonların yoğunlaşması ile yeniden dağılım süreçlerini teşvik ederek diyatomit etkilerini artırdığını göstermektedir. Genel olarak bulgular, diyatomitin toplam tuzluluk seviyelerini artırmasına rağmen, Na baskınlığını azaltarak ve Ca–Mg dengesini güçlendirerek sodisite ile ilişkili kimyasal koşulları iyileştirebilen bir mineral toprak düzenleyici olarak işlev gördüğünü ortaya koymaktadır. Sonuçlar, ayrıca diyatomitin etkinliğinin toprak nem rejimine güçlü şekilde bağlı olduğunu ve bu nedenle su yönetimi koşullarıyla birlikte değerlendirilmesi gerektiğini göstermektedir. Diyatomit, kireçli–hafif alkali topraklarda iyonik dengeyi iyileştirmek için potansiyel bir toprak düzenleyici olarak görülmektedir; ancak pratik uygunluğu, özellikle bitki tepkisi, tuzluluk riski ve uzun dönemli toprak davranışı açısından tarla koşullarında dikkatle değerlendirilmelidir.

Anahtar Kelimeler: Diyatomit, toprak nem rejimi, kireçli–hafif alkali toprak, iyonik denge, tuzluluk ve sodisite, değişebilir katyonlar, toprak çözeltisi

1. Introduction

Soil deterioration as a result of sodicity, salinity, and inadequate nutrient ratios threatens farming productivity by limiting the amount of viable land available to farmers in both arid and semi-arid areas, where irrigation is key to achieving commercial yields from crops. Problems in these types of environments are typically created when there is insufficient leaching, high rates of evaporation, and/or the use of low-quality irrigation water, all of which contribute to the accumulation of soluble Na and soluble salts found at greater depths within the soil than would otherwise be the case, which negatively affects both the chemical composition and physical structure of the soil. Recognized as one of the larger constraints to sustainable irrigated crop agriculture in dryland regions (Qadir and Oster, 2004; Murtaza et al., 2006; Daba and Qureshi, 2021; Stavi et al., 2021), these concerns will be even more critical for calcareous–alkaline soils, where the elevated pH, carbonate buffering, and prevalence of calcium (Ca)-dominated minerals affect the availability of nutrients, function of cation-exchange equilibria, and quantity/quality of the soil solution (Penn and Camberato, 2019).

In calcareous soils, phosphorus fixation, cation imbalance, and sodicity-related ionic stress represent some of the most significant chemical constraints. Phosphorus in these soils is commonly immobilized through both adsorption and precipitation reactions with Ca and Mg, thereby reducing its availability to plants. The availability of phosphorus in calcareous systems is strongly regulated by carbonate-associated geochemical processes, particularly those controlled by soil pH and $CaCO_3$ content, which influence both precipitation–dissolution equilibria and surface adsorption mechanisms (Penn and Camberato, 2019; Haynes, 1982). In addition, phosphorus availability is further modulated by the surrounding soil chemical environment, including ionic composition, organic matter interactions, and competing sorption processes (Lal, 2015). The effect of sodium (Na) on the soil solution and exchange complex can negatively affect nutrient balance and contribute to structural instability and infiltration and dispersion problems in soils (Jalali and Ranjbar, 2009; Pistocchi et al., 2017; Ziskin et al., 2024). Thus, as opposed to just decreasing the total amount of salt present in the soils, a more recent focus has been to improve the ionic composition of soils that are salty and/or chemically restricted (Qadir and Oster, 2004; Daba and Qureshi, 2021; Daba, 2025).

Mineral soil amendments have attracted growing interest over the last several years for their potential to improve the chemical function of soils in conditions of low moisture availability. Silicate-type materials that are porous (e.g., zeolite, pumice, diatomaceous earth) are receiving a lot of attention because they have a very high surface area, a lot of internal porosity, the ability to adsorb ions, and the ability to modify the retention of ions, the movement of solutes, and water movement in soils. It has been suggested that these materials can impact not only the retention of water and the transport of solutes but also the exchange of cations between the soil solution and solid phase as well as how nutrients and salts are distributed between the different fractions of the soil (Mumpton, 1999; Ramesh and Reddy, 2011). In general, research on porous mineral amendments has demonstrated that their agronomic effectiveness hinges on the nature of the physical and chemical properties of the amendment, the mineralogy of the soil, and the nature and amount of water available to the soil.

Diatomite is a naturally occurring siliceous sedimentary material derived from the fossilized frustules of diatoms and is characterized by low bulk density, high porosity, and considerable adsorption capacity. Diatomite has attracted much attention in the area of adsorbents for application in environmental media because of its properties. Research has been conducted on the use of diatomite as an adsorbent for immobilization of pollutants and treatment of drinking water (de Namor and Pawlik, 2012; Piri et al., 2021; Samani et al., 2024). The research shows that diatomite is an important factor in altering the water retention capacity, mobility of nutrient ions, and sorption of ions in the soil environment and in drastically altering the physical characteristics of the soil (Piri et al., 2021; Samani et al., 2024; Aksakal et al., 2012; Aksakal

et al., 2013). Nevertheless, compared with other porous mineral amendments, the soil chemical effects of diatomite remain insufficiently understood, particularly under conditions where soil moisture regimes strongly controls ion mobility and redistribution.

The gap in our understanding here is particularly relevant to the calcareous/alkaline soils. In these soils, amendments change the ionic nature of the soils in two ways: (1) Because of the nature of the amendment itself, and (2) Carbonate buffering, cation exchange reactions, and solute redistribution from water movement through the soil. Because diatomite is a porous siliceous material, the addition of this material will help partition ions among the exchangeable, extractable, and solution phase of what are otherwise a direct increase/decrease of the total concentration of ions. Therefore, the use of individual parameters as standalone measures may not provide sufficient information to determine the degree of change to the soil chemical properties due to the application of soil amendments; rather, it would be better to evaluate the degree of change in soil chemical properties based on the overall shift in the ionic equilibrium state of the soil, including the amounts of the following chemical components that are highly mobile within the soils: (Ca + Mg + Na + K) (bicarbonate + sulfate + chloride); because these changes directly affect soil nutrients, sodicity indicators (e.g. sodicity, SAR) and the rhizosphere chemical environment. Fractions specific to their respective phase properties exhibit similar behavior during solution interaction as well. For example, the mechanics of Ca, Mg, and K in soils have received much attention, particularly in studies examining the kinetics involved and the definition of operationally "available" pools versus their true distribution across different soil phases (Bel et al., 2020).

Additionally, the expression of chemical processes in soil may be affected by soil moisture regimes. For example, both deficit irrigation and limited water movement may cause an increase in the concentration of soluble ions through the leaching of soluble ions, while increased moisture may lead to a dilution of soluble ions and downward migration of soluble ions. Therefore, soil moisture regimes function as a water management variable, and also as a key factor in determining the transport, concentration, and exchange of ions in the soil. Thus, the combined effects of soil moisture regimes and diatomite are expected to result in changes in salinity, as well as alterations in the relationship between salinity and sodicity in addition to a redistribution of nutrients and ions in the variously defined soil fractions (Murtaza et al., 2006; Jalali and Ranjbar, 2009; Qiao et al., 2026).

Despite this mechanistic relevance, limited information is available on how diatomite interacts with different soil moisture regimes to influence soil chemical properties, exchangeable cation composition, and soil solution ionic dynamics in calcareous soils. Most previous studies have focused primarily on contaminant sorption, water retention, or plant growth, while the integrated response of soil chemical and ionic parameters under diatomite application remains poorly documented. In particular, it remains unclear whether diatomite acts primarily by increasing total soluble salts, by modifying ionic balance, or by redistributing nutrients and salts among soil fractions under different moisture regimes.

Therefore, the objective of this study was to evaluate the effects of different diatomite application rates and soil moisture regimes on soil chemical properties, available nutrients, exchangeable cations, and water-soluble ions in a calcareous-slightly alkaline soil. I hypothesized that diatomite would not simply increase or decrease salinity-related parameters uniformly, but would instead alter the ionic equilibrium of the soil system through redistribution processes that are strongly regulated by soil moisture regimes. Understanding these interactions is essential for assessing the agronomic and ameliorative potential of diatomite under water-limited soil management conditions.

2. Materials and Methods

2.1. Soil Sampling and Analytical Methods

The initial properties of the soil used in the experiment are presented in Table 1. Soil samples representative of the experimental field were taken prior to performing any experiments, then air-dried, crushed gently to pass through a sieve (2 mm) for analysis. Soil physical and chemical properties were initially determined using standard laboratory methods. Soil texture was determined using the hydrometer method (Bouyoucos, 1962). Soil pH and electrical conductivity (EC) were measured on the saturation extract, with pH determined using a glass electrode and EC derived from conductivity using Richards (1954) methodology. The total soluble salt content (%) was quantified using EC values according to normal salinity interpretations (Richards, 1954). Calcium carbonate ($CaCO_3$) content was determined by the Scheibler calcimeter method based on volumetric measurement of CO_2 released after acid treatment (Soil Survey Staff, 2014). Soil organic matter (OM) was determined by the modified Walkley–Black wet oxidation method (Rowell, 1996). Available phosphorus (P) was extracted using the sodium bicarbonate method and determined colorimetrically, which is considered appropriate for calcareous soils (Olsen et al., 1954). Available potassium (K), calcium (Ca), and magnesium (Mg) were extracted with neutral ammonium acetate (1 N NH_4OAc, pH 7.0). K was determined by flame photometry, whereas Ca and Mg were measured by ICP-OES according to standard procedures (Jackson, 1958). Water-soluble Ca, Mg, Na, K, CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-} were determined in the soil saturation extract prepared according to Richards (1954). Soluble Ca and Mg were measured by titration with EDTA; soluble Na and K were determined by flame photometry; CO_3^{2-} and HCO_3^- were determined by titration; chloride (Cl^-) was measured by silver nitrate titration; and sulfate (SO_4^{2-}) was determined turbidimetrically or by standard gravimetric/turbidimetric procedures as described by Richards (1954). Exchangeable Ca, Mg, Na, and K were extracted with 1 N ammonium acetate (NH_4OAc, pH 7.0). Exchangeable Ca and Mg were determined by ICP-OES, while exchangeable Na and K were measured by flame photometry (Thomas, 1982). Cation exchange capacity (CEC) was determined based on ammonium saturation and replacement procedures using ammonium acetate extraction (Bower, 1952). The sodium adsorption ratio (SAR) was calculated from the concentrations of soluble Na^+, Ca^{2+}, and Mg^{2+} in the saturation extract using the following equation 1:

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \qquad \text{……..(1)}$$

where ionic concentrations are expressed in meq L^{-1} (Richards, 1954).

Table 1. The initial properties of the soil used in the experiment

Soil Properties	Results	Soil Properties	Results
Texture Class	Clay Loam (CL)	Water-soluble Ca (meq L^{-1})	2.01
Sand (%)	24.6	Water-soluble Mg (meq L^{-1})	2.81
Silt (%)	35.9	Water-soluble Na (meq L^{-1})	2.28
Clay (%)	39.5	Water-soluble K (meq L^{-1})	0.21
Field capacity (%)	32.80	Water-soluble CO_3 (meq L^{-1})	0.00
Permanent wilting point (%)	15.68	Water-soluble HCO_3 (meq L^{-1})	2.88
EC (dS m^{-1})	0.67	Water-soluble Cl (meq L^{-1})	2.74
Salt (%)	0.04	Water-soluble SO_4 (meq L^{-1})	1.68
pH	7.74	Exchangeable Ca (%)	63.03
Lime ($CaCO_3$) (%)	31.51	Exchangeable Mg (%)	33.3
Organic Matter (%)	0.81	Exchangeable Na (%)	2.37
Available P_2O_5 (kg ha^{-1})	57.48	Exchangeable K (%)	1.30
Available K_2O (kg ha^{-1})	536.26	Cation exchange capacity (meq 100 g^{-1})	24.02
Available Calcium (Ca) (ppm)	5400	Sodium adsorption ratio (SAR)	1.47
Available Magnesium (Mg) (ppm)	1625		

2.2. Properties of Diatomite

The specific surface area of diatomite was determined by the Sears titration method (Sears, 1956). The pH of the material was measured in a 1:5 (w/v) diatomite-to-water suspension (Thomas, 1996). Cation exchange capacity (CEC) was determined using the ammonium acetate saturation method (Sumner and Miller, 1996). Its specific surface area, pH, and CEC were determined as 59.17 $m^2\ g^{-1}$, 8.16, and 62.10 cmol kg^{-1}, respectively.

2.3. Greenhouse Experimental Design

The greenhouse experiment was conducted at the Soil Fertilizer and Water Resources Central Research Institute in Ankara, Türkiye (39°57′16.38″ N; 32°48′44.47″ E). The study was carried out under controlled greenhouse conditions to evaluate the effects of different diatomite application rates and soil moisture regimes on the chemical properties and ionic composition of a calcareous–slightly alkaline soil. The experiment was established as a pot study based on a completely randomized design with three replications. The experimental treatments consisted of three diatomite doses and three soil moisture regimes. Diatomite was applied to the soil at rates of 0%, 15%, and 30% (v/v), hereafter referred to as DT0, DT15, and DT30, respectively. The soil moisture regimes were set at 100%, 60%, and 40% of field capacity, hereafter referred to as FC100, FC60, and FC40, respectively. Accordingly, the experiment included a total of nine treatment combinations (3 × 3). Before pot filling, the air-dried and sieved soil was thoroughly mixed with the designated amount of diatomite to ensure homogeneous distribution within each treatment. The treated soils were then transferred into pots, and the initial soil moisture content was adjusted to the corresponding soil moisture regime. Throughout the experimental period, soil moisture was maintained at the target levels by periodic weighing of the pots and replenishment of water losses. The pots were arranged randomly in the greenhouse to minimize positional effects, and all treatments were maintained under identical environmental conditions throughout the experimental period. At the end of the incubation period, soil samples were collected from each pot and analyzed for soil chemical properties, available nutrients, exchangeable cations, and water-soluble ions.

2.4. Statistical Analysis

IBM SPSS Statistics version 25.0 was used for all the analyses. The analysis of applications began with the application of analysis of variance (ANOVA). Where applicable, Duncan's multiple range test has been used for mean comparisons at a relevant significance level. The correlation between parameters were generated using OriginPro 2025b software (OriginLab Inc., Northampton, MA, USA).

3. Results

3.1. Basic Soil Chemical Properties

The analysis of variance and the effects of diatomite application rates and soil moisture regimes on the basic soil chemical properties are presented in Tables 2 and 3. Diatomite application and soil moisture regime produced parameter-dependent effects on the investigated soil chemical properties. According to the analysis of variance, the DT × SMR interaction was statistically significant for pH, EC, salt content, and $CaCO_3$, whereas OM was affected mainly by the main effect of diatomite dose. Soil pH was not significantly affected by the main effects of diatomite dose or soil moisture regime; however, the DT × SMR interaction was significant. Soil pH values generally remained within the alkaline range and varied between 7.03 and 8.01. The highest pH value was recorded in the DT15FC40 treatment (8.01), whereas the lowest value was observed in DT15FC100 (7.03). Despite the significant interaction, the overall variation in pH among treatments was relatively narrow. In contrast, both EC and salt content were significantly affected by diatomite dose, soil moisture regime, and their interaction. EC values ranged from 0.51 to 5.57 dS m^{-1}, while salt content ranged from 0.03 to 0.36%. The highest values for both parameters were obtained under the DT30FC60 combination (EC = 5.57 dS m^{-1}; Salt = 0.36%). Regarding the main effect of diatomite, EC increased from 1.15 dS m^{-1}

in DT0 to 2.79 dS m^{-1} in DT15 and 3.32 dS m^{-1} in DT30. Similarly, salt content increased with increasing diatomite dose. For the soil moisture regime main effect, the highest EC and salt content were observed under FC60 (3.46 dS m^{-1} and 0.22%, respectively). Soil $CaCO_3$ content also showed significant variation depending on treatment combinations and ranged from 28.3 to 31.9%. The highest $CaCO_3$ value was recorded in DT0FC100 (31.9%), whereas the lowest was found in DT15FC100 (28.3%). At the main-effect level, DT0 (31.1%) had the highest $CaCO_3$ content, while DT15 (29.3%) had the lowest. On the other hand, OM was affected only by diatomite dose. OM values were 0.86% in DT0 and 0.78% in both DT15 and DT30, while treatment means ranged from 0.72 to 0.89%.

Table 2. Analysis of Variance Showing the Effects of Diatomite Application (DT), Soil Moisture Regime (SMR), and their Interaction (DT × SMR) on Basic Soil Chemical Properties and Available Nutrients after the experimental period

VS	df	pH		EC		Salt, %		$CaCO_3$, %		OM, %	
		F	P	F	P	F	P	F	P	F	P
DT	2	0.38	0.38	6.89	0.00	6.95	0.00	6.26	0.01	3.93	0.04
SMR	2	0.23	0.23	8.35	0.00	8.73	0.00	0.80	0.47	3.16	0.07
DT x SMR	4	0.00	0.00	3.54	0.03	3.78	0.02	3.88	0.02	1.53	0.24
Error	16	0.058		1.657		0.007		1.295		0.005	
Total	27	1522.4		261.7		1.064		24330.31		17.61	
VC, %		4.57		8.25		8.28		5.18		10.41	
VS	df	Av. P_2O_5, kg ha^{-1}		Av. K_2O, kg ha^{-1}		Av. Ca, ppm		Av. Mg, ppm			
		F	P	F	P	F	P	F	P		
DT	2	1.99	0.17	6.06	0.01	5.66	0.01	14.59	0.00		
SMR	2	5.97	0.01	0.18	0.84	4.54	0.03	10.72	0.00		
DT x SMR	4	4.72	0.01	0.57	0.69	4.95	0.00	12.47	0.00		
Error	16	3.210		47.49		601613		28068			
Total	27	1016.62		82921		883436103		70201548			
VC, %		4.52		14.04		2.01		2.25			

VS: Variation Sources, df: Degrees of Freedom, DT: Diatomite, SMR: Soil Moisture Regime, VC: Coefficient of Variation, Av: Available

Table 3. Effects of Diatomite Application and Soil Moisture Regimes on Basic Soil Chemical Properties and Available Nutrients after the Experimental Period

Treatments	pH	EC	Salt, %	$CaCO_3$, %	OM, %	Av. P_2O_5, kg ha^{-1}	Av. K_2O, kg ha^{-1}	Av. Ca, ppm	Av.Mg, ppm
DT0FC100	7.51 abc	0.92 c	0.06 d	31.9 a	0.86	45 cd	637	6002 a	1703 ab
DT0FC60	7.80 ab	1.35 c	0.09 cd	31.4 ab	0.82	41 cd	588	6198 a	1653 b
DT0FC40	7.44 abc	1.19 c	0.08 cd	29.9 abc	0.89	56 bc	617	6077 a	1643 b
DT15FC100	7.03 c	4.39 ab	0.28 ab	28.3 c	0.82	69 ab	533	5494 a	1552 b
DT15FC60	7.45 abc	3.46 abc	0.22 bc	29.0 bc	0.78	95 a	492	5780 a	1764 ab
DT15FC40	8.01 a	0.51 c	0.03 d	30.7 ab	0.74	30 d	541	6170 a	1862 a
DT30FC100	7.68 ab	2.95 bc	0.19 bc	29.2 bc	0.87	77 ab	509	5844 a	1647 b
DT30FC60	7.22 bc	5.57 a	0.36 a	30.7 ab	0.72	60 bc	541	2995 b	690 c
DT30FC40	7.37 abc	1.43 c	0.09 cd	28.7 bc	0.74	32 d	484	5909 a	1655 b
DT, %									
DT0	7.58	1.15 b	0.07 b	31.1 a	0.86 a	48	614 a	6092 a	1667 a
DT15	7.50	2.79 ab	0.18 ab	29.3 b	0.78 b	65	522 b	5815 a	1726 a
DT30	7.42	3.32 a	0.21 a	29.5 ab	0.78 b	56	511 b	4916 b	1331 b
SMR, %									
FC100	7.41	2.76 ab	0.17 ab	29.8	0.85	64 a	559	5780 a	1634 a
FC60	7.49	3.46 a	0.22 a	30.4	0.77	65 a	540	4991 b	1369 b
FC40	7.61	1.05 b	0.07 b	29.8	0.79	39 b	547	6052 a	1720 a

DT: Diatomite, SMR: Soil Moisture Regime, FC: Field capacity, EC: Electrical Conductivity, OM: Organic

3.2. Available Nutrients

The analysis of variance and the effects of diatomite application rates and soil moisture regimes on the available nutrients are presented in Tables 2 and 3. Diatomite and soil moisture regimes significantly affected the availability of several essential nutrients, although the response pattern varied among elements. Available P_2O_5, Ca, and Mg showed significant treatment responses, whereas available K_2O was influenced mainly by diatomite dose. Available P_2O_5 was significantly affected by soil moisture regimes and the DT × SMR interaction, with values ranging from 30 to 95 kg ha^{-1}. The highest available P_2O_5 value was obtained in DT15FC60 (95 kg ha^{-1}), whereas the lowest was observed in DT15FC40 (30 kg ha^{-1}). At the main-effect level, available P_2O_5 values were 48, 65, and 56 kg ha^{-1} for DT0, DT15, and DT30, respectively. In terms of soil moisture regimes, FC100 and FC60 produced similar and higher values (64 and 65 kg ha^{-1}, respectively), whereas FC40 resulted in a lower value (39 kg ha^{-1}). Available K_2O was significantly affected only by diatomite dose and generally decreased with increasing diatomite application. The mean available K_2O values were 614, 522, and 511 kg ha^{-1} for DT0, DT15, and DT30, respectively. The highest value was recorded in DT0FC100 (637 kg ha^{-1}), whereas the lowest was observed in DT30FC40 (484 kg ha^{-1}). Available Ca and Mg were significantly affected by diatomite dose, soil moisture regimes, and the DT × SMR interaction. Available Ca values ranged from 2995 to 6198 ppm, while available Mg values ranged from 690 to 1862 ppm. For both nutrients, the lowest values were observed under DT30FC60 (available Ca = 2995 ppm; available Mg = 690 ppm). At the main-effect level, available Ca decreased from 6092 ppm in DT0 to 5815 ppm in DT15 and 4916 ppm in DT30. Likewise, available Mg values were 1667, 1726, and 1331 ppm for DT0, DT15, and DT30, respectively. The lowest soil moisture regimes means for both available Ca and Mg were recorded under FC60 (4991 and 1369 ppm, respectively).

3.3. Exchangeable Cations, Cation Exchange Capacity and Sodium Adsorption Ratio

The analysis of variance and the effects of diatomite application rates and soil moisture regimes on the exchangeable cations, cation exchange capacity and sodium adsorption ratio are presented in Tables 4 and 5. The exchangeable cation composition of the soil was markedly altered by diatomite application. Exchangeable Ca, Mg, Na, and K responded significantly to diatomite dose, while SAR was significantly affected by both diatomite dose and the DT × SMR interaction. Exchangeable Ca increased with increasing diatomite dose, with mean values of 65.54% in DT0, 78.75% in DT15, and 84.66% in DT30. Among treatment combinations, the highest exchangeable Ca value was recorded in DT30FC60 (88.47%), whereas the lowest was found in DT0FC100 (62.19%). In contrast, exchangeable Mg decreased with diatomite application, with values of 30.52% in DT0, 17.81% in DT15, and 12.47% in DT30. A similar decreasing trend was observed for exchangeable Na and K. Exchangeable Na decreased from 2.34% in DT0 to 1.57% in DT15 and 1.56% in DT30. The highest exchangeable Na value was observed in DT0FC60 (2.93%), whereas the lowest was recorded in DT30FC60 (1.35%). Exchangeable K also declined, with average values of 1.60, 1.31, and 1.31% for DT0, DT15, and DT30, respectively. CEC increased significantly with diatomite application. Mean CEC values were 23.13, 23.05, and 24.43 meq 100 g^{-1} for DT0, DT15, and DT30, respectively. The highest CEC value was observed in DT30FC100 (25.06 meq 100 g^{-1}), whereas the lowest was found in DT15FC100 (22.70 meq 100 g^{-1}). The SAR, one of the key sodicity indicators, was significantly affected by both diatomite dose and the DT × SMR interaction. SAR values ranged from 0.35 to 3.18, with the highest value recorded in DT0FC60 (3.18) and the lowest in DT30FC60 (0.35). At the main-effect level, SAR values were 2.03 in DT0, 0.61 in DT15, and 0.59 in DT30, indicating a substantial decline in sodicity-related risk with increasing diatomite dose.

Table 4. Analysis of Variance Showing the Effects of Diatomite Application (DT), Soil Moisture Regime (SMR), and their Interaction (DT × SMR) on Exchangeable Cations, CEC, and SAR after the experimental period

VS	df	Exc. Ca, %		Exc. Mg, %		Exc. Na, %	
		F	P	F	P	F	P
DT	2	20.4	0.00	22.11	0.00	9.39	0.00
SMR	2	1.25	0.31	1.51	0.25	0.34	0.72
DT x SMR	4	1.58	0.23	1.36	0.29	2.48	0.09
Error	16	42.279		34.990		0.192	
Total	27	160042.5		13506.0		98.72	
VC, %		13.58		4.76		3.19	
VS	df	Exc. K, %		CEC, meq 100 g^{-1}		SAR	
		F	P	F	P	F	P
DT	2	5.88	0.01	3.82	0.04	14.02	0.00
SMR	2	0.14	0.87	0.63	0.54	1.63	0.23
DT x SMR	4	0.53	0.72	1.15	0.37	3.21	0.04
Error	16	0.043		1.418		0.437	
Total	27	54.94		15004.6		57.96	
VC, %		16.14		5.47		9.43	

VS: Variation Sources, df: Degrees of Freedom, DT: Diatomite, SMR: Soil Moisture Regime, VC: Coefficient of Variation, Exc: Exchangeable, CEC: Cation Exchange Capacity, SAR: Sodium Adsorption Ratio

Table 5. Effects of Diatomite Application (DT) and Soil Moisture Regimes (SMR) on Exchangeable Cations, Cation Exchange Capacity and Sodium Adsorption Ratio after the Experimental Period

Treatments	Exc. Ca, %	Exc. Mg, %	Exc. Na, %	Exc. K, %	CEC, meq 100 g^{-1}	SAR
DT0FC100	62.19	34.17	2.03	1.60	23.04	1.32 ab
DT0FC60	64.96	30.61	2.93	1.51	23.42	3.18 b
DT0FC40	69.46	26.76	2.07	1.70	22.94	1.58 ab
DT15FC100	80.24	17.01	1.47	1.28	22.70	0.44 c
DT15FC60	83.78	13.50	1.42	1.30	22.98	0.44 c
DT15FC40	72.23	22.91	1.83	1.36	23.48	0.95 bc
DT30FC100	81.04	15.99	1.70	1.28	25.06	0.55 c
DT30FC60	88.47	8.79	1.35	1.40	23.19	0.35 c
DT30FC40	84.48	12.64	1.63	1.25	25.05	0.87 bc
DT, %						
DT0	65.54 b	30.52 a	2.34 a	1.60 a	23.13 b	2.03 a
DT15	78.75 a	17.81 b	1.57 b	1.31 b	23.05 b	0.61 b
DT30	84.66 a	12.47 b	1.56 b	1.31 b	24.43 a	0.59 b
SMR, %						
FC100	74.49	22.39	1.73	1.39	23.60	0.77
FC60	79.07	17.63	1.90	1.40	23.20	1.32
FC40	75.39	20.77	1.84	1.44	23.82	1.13

DT: Diatomite, SMR: Soil Moisture Regime, FC: Field capacity, Exc: Exchangeable, CEC: Cation Exchange Capacity, SAR: Sodium Adsorption Ratio

3.4. Water-Soluble Ions and Soil Solution Chemistry

The analysis of variance and the effects of diatomite application rates and soil moisture regimes on the water-soluble ions are presented in Tables 6 and 7. Among all measured variables, the ionic composition of the soil solution showed some of the clearest treatment responses. WS-Ca, WS-Mg, WS-K, and WS-SO_4 were significantly influenced by the DT × SMR interaction, while WS-Na, WS-HCO_3, and WS-Cl were mainly affected by diatomite dose. WS-Ca and WS-Mg were significantly affected by diatomite dose, soil moisture regimes, and their interaction. WS-Ca values ranged from 3.12 to 27.83 meq L^{-1}, while WS-Mg values ranged from 1.23 to 24.51 meq L^{-1}. The highest values for both parameters were observed under the DT30FC60 combination (WS-Ca = 27.83 meq L^{-1}; WS-Mg = 24.51 meq L^{-1}). At the main-

effect level, WS-Ca values were 3.46, 13.50, and 16.49 meq L^{-1} for DT0, DT15, and DT30, respectively, while WS-Mg values were 4.29, 12.45, and 14.52 meq L^{-1}. In terms of soil moisture regimes, the highest means for both parameters were obtained under FC60 (16.03 and 14.87 meq L^{-1}, respectively). WS-Na was significantly affected only by diatomite dose, with mean values of 3.92 meq L^{-1} in DT0 and 1.67 meq L^{-1} in both DT15 and DT30. Among treatment combinations, the highest WS-Na value was recorded in DT0FC60 (6.03 meq L^{-1}), whereas the lowest was observed in DT15FC40 (1.40 meq L^{-1}). For WS-K, the DT × SMR interaction was significant, and values ranged from 0.22 to 0.54 meq L^{-1}. The highest WS-K value was found in DT30FC60 (0.54 meq L^{-1}), while the lowest was recorded in DT30FC40 (0.22 meq L^{-1}). WS-HCO_3 was affected only by diatomite dose, with mean values of 2.59, 2.16, and 1.75 meq L^{-1} for DT0, DT15, and DT30, respectively. The highest WS-HCO_3 value was recorded in DT15FC40 (3.06 meq L^{-1}), whereas the lowest was observed in DT30FC60 (1.36 meq L^{-1}). WS-Cl also decreased with diatomite application, with mean values of 4.49, 2.23, and 2.13 meq L^{-1} for DT0, DT15, and DT30, respectively. The highest WS-Cl value was found in DT0FC60 (6.50 meq L^{-1}), whereas the lowest was observed in DT30FC60 (1.96 meq L^{-1}). WS-SO_4 was significantly affected by diatomite dose, soil moisture regimes, and the DT × SMR interaction. Values ranged from 0.43 to 51.30 meq L^{-1}, with the highest value recorded in DT30FC60 (51.30 meq L^{-1}) and the lowest in DT15FC40 (0.43 meq L^{-1}). At the main-effect level, WS-SO_4 increased from 4.89 meq L^{-1} in DT0 to 23.62 meq L^{-1} in DT15 and 29.26 meq L^{-1} in DT30. For soil moisture regimes, the corresponding values were 23.52, 29.05, and 5.20 meq L^{-1} for FC100, FC60, and FC40, respectively. Overall, the most pronounced treatment-induced changes in many soil chemical and soil solution parameters were observed under the FC60 soil moisture regime.

Table 6. Analysis of Variance Showing the Effects of Diatomite Application (DT), Soil Moisture Regime (SMR), and their Interaction (DT × SMR) on Water-Soluble Ions after the Experimental Period

VS	df	WS-Ca, meq L^{-1}		WS-Mg, meq L^{-1}		WS-Na, meq L^{-1}		WS-K, meq L^{-1}	
		F	P	F	P	F	P	F	P
DT	2	9.94	0.00	8.68	0.00	11.7	0.00	2.86	0.09
SMR	2	7.09	0.00	10.57	0.00	2.13	0.15	2.86	0.09
DT x SMR	4	3.31	0.04	4.16	0.02	3.02	0.06	3.67	0.03
Error	16	42.168		30.365		1.304		0.008	
Total	27	6113.2		5141.6		232.6		3.762	
VC, %		9.23		8.85		6.99		3.22	
VS	df	WS-HCO_3, meq L^{-1}		WS-Cl, meq L^{-1}		WS-SO_4, meq L^{-1}			
		F	P	F	P	F	P		
DT	2	4.13	0.04	7.97	0.00	9.51	0.00		
SMR	2	3.50	0.06	1.58	0.24	9.11	0.00		
DT x SMR	4	1.38	0.28	1.91	0.16	3.73	0.03		
Error	16	0.380		2.008		153.942			
Total	27	141.5		322.8		20731.9			
VC, %		3.45		6.23		10.55			

VS: Variation Sources, df: Degrees of Freedom, DT: Diatomite, SMR: Soil Moisture Regime, VC: Coefficient of Variation, WS: Water-soluble

Table 7. Effects of Diatomite Application (DT) and Soil Moisture Regimes (SMR) on Water-Soluble Ions after the Experimental Period

Treatments	WS-Ca, meq L^{-1}	WS-Mg, meq L^{-1}	WS-Na, meq L^{-1}	WS-K, meq L^{-1}	WS-CO_3, meq L^{-1}	WS-HCO_3, meq L^{-1}	WS-Cl, meq L^{-1}	WS-SO_4, meq L^{-1}
DT0FC100	3.14 c	4.42 c	2.52	0.32 bc	0.00	2.68	2.83	4.89 d
DT0FC60	3.27 c	4.09 c	6.03	0.27 cd	0.00	2.41	6.50	4.75 d
DT0FC40	3.97 c	4.35 c	3.22	0.31 bc	0.00	2.68	4.14	5.03 d
DT15FC100	20.37 ab	20.11 ab	1.97	0.44 ab	0.00	1.53	2.03	39.34 ab
DT15FC60	17.00 ab	16.01 ab	1.64	0.37 abc	0.00	1.90	2.03	31.09 abc
DT15FC40	3.12 c	1.23 c	1.40	0.36 abc	0.00	3.06	2.63	0.43 d
DT30FC100	14.36 b	13.74 b	1.78	0.38 abc	0.00	1.82	2.11	26.34 bcd
DT30FC60	27.83 a	24.51 a	1.51	0.54 a	0.00	1.36	1.96	51.30 a
DT30FC40	7.29 bc	5.32 c	1.71	0.22 d	0.00	2.08	2.32	10.14 cd
DT, %								
DT0	3.46 b	4.29 b	3.92 a	0.30	0.00	2.59 a	4.49 a	4.89 b
DT15	13.50 a	12.45 a	1.67 b	0.39	0.00	2.16 ab	2.23 b	23.62 a
DT30	16.49 a	14.52 a	1.67 b	0.38	0.00	1.75 b	2.13 b	29.26 a
SMR, %								
FC100	12.62 ab	12.76 a	2.09	0.38	0.00	2.01	2.32	23.52 a
FC60	16.03 a	14.87 a	3.06	0.39	0.00	1.89	3.50	29.05 a
FC40	4.79 b	3.63 b	2.11	0.30	0.00	2.61	3.03	5.20 b

DT: Diatomite, SMR: Soil Moisture Regime, FC: Field capacity, WS: Water-soluble

4. Discussion

4.1. Effects of Diatomite Application and Soil Moisture Regimes on Basic Soil Chemical Properties

The results of the research demonstrate conclusive evidence supporting that diatomite acted as a chemically active material, not just as an inert mineral additive, and had the ability to change soil ionic equilibria and change the composition of soil solutions. This active role of diatomite aligns with the inherent physicochemical characteristics of diatomite, such as its siliceous structure, porous morphology, large reactive surface area, and capacity for adsorption/ion retention. Samani et al. (2024) have reported similar mechanisms and characteristics on natural diatomite and diatomite modified with other materials, and observed these sorptive capacities and strong affinity for ionic species. Samani et al. (2024) reported that modified diatomite can alter the chemical behaviour of soils through processes associated with adsorption and redistribution of chemical species.

The increased levels of EC and salinity will be more significant under treatment DT30FC60 than any other treatment. Therefore, the increase in the amount of soluble ions in the soil solution was attributed to the contribution of ionic inputs from the amendment and the reduction in leaching as a result of the moderate water deficit. In saline and irrigated systems, the accumulation of dissolved salts is influenced by an equilibrium between the release of ions into solution and the downward movement of water within the soil. As stated by Stavi et al. (2021), saline soil development in semi-arid and irrigated soils is influenced not only by the amount of salt added to the soil but also by water use management practices and the impact of evapoconcentration on developing soil salinity. Additionally, Qadir et al. (2006) and Rengasamy (2010) noted that the assessment of soil salinity should consider not only the total amount of soluble salts present in the solution but also the ionic composition of that solution and how salinity is affected by sodicity.

Soil pH remained in a narrow range towards alkaline despite significant DT × SMR interaction which indicates that DT x SMR pH responses were not 100% independent of treatment combination. In calcareous soils it is common for pH to be buffered by carbonate

equilibria which limits the potential of large-scale pH movements unless both the treatment affects the dissolution–precipitation dynamic and/or generates protons/basis. Therefore, stable pH observed at all times in these experiments remains consistent with the buffering capability of calcareous soils. Lindsay (1979) and Sparks (2003) noted that high levels of $CaCO_3$-rich soils usually have alkaline pH values regardless of changes in solution ionic strength and nutrient flux. Variability in the amount of $CaCO_3$ for treatment may also indicate minor changes in the equilibrium of carbonate materials instead of direct mineral gaining or losing.

The decreased organic matter observed within the samples with increasing amounts of diatomite will likely be associated with a dilution effect rather than a direct stimulation of decomposition. Because diatomite is a mineral addition and does not supply organic carbon to the environment, its application may only serve to increase the proportion of minerals in relation to organics within the soil environment. Therefore, the decreases in organic matter should be interpreted cautiously and not necessarily as evidence of accelerated degradation of organic matter.

4.2. Effects of Diatomite Application and Soil Moisture Regimes on Available Nutrients

The significant influence of diatomite application rates and soil moisture regimes on available P_2O_5 suggests that both the amount of diatomite applied and the moisture in the soil influenced phosphorus availability. This is an important point in calcareous soils since phosphorus is often temporarily immobilized in calcareous soils by precipitation as Ca phosphates, adsorption onto surfaces, and slow diffusion. Soil moisture influences the dissolution, diffusion, and movement of phosphorus to the rhizosphere in these environments. The high level of P_2O_5 observed for the DT15FC60 soil samples indicates that moderate levels of moisture may promote a balance between mobilizing P and reducing its risk of leaching away. Hinsinger (2001), Lindsay (1979) and von Wandruszka (2006) also reported that P availability in calcareous soils is very sensitive to both the type of amendments applied and the soil moisture content. According to von Wandruszka (2006), the retention of phosphorus within calcareous soils relies principally upon the mechanisms of sorption (the acid forming) or precipitation (the carbonate forming), both of which will respond rapidly and to any changes occurring in either their chemical or hydrological properties.

The response of K was more complicated. Although K_2O available to be taken up from the soil and the amount of exchangeable K in the soil generally decreased with greater amounts of diatomite, however, WS-K had a clear interaction in the growth response. So, K was not only removed by being used by plants but it was also moved around between different parts of the soil. The way K behaves in soils, is highly related to cation competition and the selectivity of the exchange site. Since there will be higher concentrations of both Ca^{2+} and Mg^{2+} ions in the exchange space; it will cause K^+ ions to either be relocated from that exchange site or placed in less available forms. This statement is supported by the work carried out by Jalali (2008), Jalali found that the kinetics and exchange characteristics of K are greatly affected both by the presence of Na and Mg, and also supported by Sparks (2003) demonstrated that the replacement of exchangeable Ca, Mg and K can have an impact on cation competition and therefore affect the availability of all three nutrient elements in soils. Therefore, the K response observed in the present study would appear to be due either to changes in competitive ion exchange or the movement of ions through operationally defined exchange sites as opposed to an overall reduction in K content.

The difference in behavior between available and actually water-soluble forms of Ca or Mg is a key result of the current study. The amount of available Ca and Mg was reduced when the soil was subjected to DT30FC60, but the water-soluble forms increased dramatically. This strongly suggests that neither Ca nor Mg were lost from these systems and were instead distributed among different soil fractions. Therefore, it can be determined that neither Ca nor

Mg are located within a single fraction of soil and exist in all three forms: exchangeable, extractable and in soil solution. Thus, the researchers can conclude that diatomite created a migration of Ca and Mg into the soil solution, especially when the soil is on a moderate water-deficiency condition (Bel et al., 2020). Bel et al. (2020) have demonstrated that conventional extraction techniques might lead to an underestimation of the amount of Ca, Mg, and K available for uptake by plants since the plant use these three elements from both the solid and liquid phases of the soil. Furthermore, they found that the addition of diatomite to soil has the potential to changed the distribution of ions between operationally defined fractions of the soil through sorption and redistribution (Piri et al., 2021).

Mg^{2+} should be of particular concern since it has exhibited a different reaction to soil systems than what is seen for Ca^{2+}. In addition to both being divalent cations, Mg^{2+} has a greater hydration energy and can interact differently with clay, soil structure and chemistry in solution from what Ca^{2+} does. Rengasamy (2010) and Sparks (2003) have shown that under certain circumstances Mg^{2+} will create a greater effect on structural behaviour of soil than will Ca^{2+} do; thus, part of the explanation of the apparent more dynamic behaviour of the Mg within this study across the different pools (available; exchangeable; water soluble).

4.3. Effects of Diatomite Application and Soil Moisture Regimes on Exchangeable Cations, Cation Exchange Capacity and Sodium Adsorption Ratio

The most important result of the study was that there were significant changes in the types of exchangeable cations (ions able to be exchanged between soil particles and soil solution) after applying diatomite. In particular, the results showed an increase in exchangeable Ca, while the amount of exchangeable Mg, Na, and K tend to decrease. This showed that the application of diatomite greatly changes the exchange character of the soil. These types of significant cation exchanges are what would be expected when adding highly porous mineral amendments that would increase available surface for cation sorption and thus alter the cation exchange equally.

From the point of view of both soil quality and sodicity risk, the loss of exchangeable Na, WS-Na and SAR is the most significant component of these responses. Soil degradation by sodicity is driven not only by total salt concentration but also by the proportion of Na compared to other cations (with divalent cations such as Ca and Mg) that are present in both the exchange complex and e of the soil solution. Having a high concentration of Na in the soil solution causes clay particles to disperse, aggregate structure instability, reduced infiltration rates and poor hydraulic conductivity. Long-term degradation of soils with sodic conditions has been shown by Stavi et al., (2021), as being often more damaging than solely having saline soils and also seems to be closely tied to the relationships between Na, Ca, and Mg in the soil, which affects both dispersion and aggregation.

Exchangeable Ca increased and exchangeable Na decreased simultaneously, indicating that Na^{+}/Ca^{2+} exchange was a key operating mechanism in the amended soil. This is consistent with findings of Pistocchi et al. (2017), which showed that amending with Ca-rich materials significantly decreases the % exchangeable Na in saline-sodic soils by displacing Na from exchange sites. This distinction is important because sodicity can be more damaging than salinity alone in structurally sensitive soils (Qadir and Oster, 2004; Rengasamy, 2010). In the current study, DT30FC60 had the lowest SAR, reflecting high contributions of soluble and exchangeable Ca and Mg (Table 3). Therefore, diatomite not only increased the total ionic load of the soil solution but also shifted the composition toward a Ca and Mg dominated system. From the perspective of impacts on soil quality, this distinction is important because sodicity can be more damaging than salinity alone in many of the calcareous and structurally fragile soils.

The CEC increase associated with diatomite application lends evidence to the manner via which diatomite modified the ion retention environment of the soil. The magnitude of this

increase in the CEC is moderate; however, it does indicate that an additional reactive area and exchangeability sites were generated by this amendment. Other porous aluminosilicate and silicate-based amendments have also demonstrated similar behavior. For example, Ming and Mumpton (2003) and Hazrati et al. (2017) pointed out that porous mineral amendments such as zeolitic materials enhance cation exchange ability and alter the ratio of exchangeable ions in the soil. As a result, the increase in CEC measured in this study supports the idea that porous mineral amendments can affect both nutrient content and the physicochemical buffering capacity of the soil.

4.4. Effects of Diatomite Application and Soil Moisture Regimes on Water-Soluble Ions and Soil Solution Chemistry

The ion makeup of the soil solution showed some of the strongest responses in terms of mechanism with respect to diatomite application and moisture regime from this study. The strongest responses were seen for both WS-Ca and WS-Mg under the combined effect of diatomite and soil moisture; with the greatest concentrations seen at DT30FC60. The detected response pattern is consistent with a system where divalent cations are increasing in concentration due to both redistribution from amendments and decreased leaching.

Increased levels of WS-Ca and WS-Mg represent an important contribution to the reason for why SAR decreases significantly. Increased amounts of water soluble Ca and Mg in the solution will decrease the SAR of a given soil when comparing the amount of Na relative to amounts of Ca and Mg. Increasing amounts of water-soluble Ca and Mg will therefore lower the SAR but may also increase overall salinity. Thus, the highest EC values were achieved with the DT30FC60 treatment and resulted in the most improved sodicity-related effects on the treated soils. Studies conducted on saline and sodic soils using amendment-based methods have similarly demonstrated that increasing amounts of soluble-phase Ca decrease the dominance of Na. Qadir and Oster (2004) and Rengasamy (2010) showed that the risk of destroying soil structure is primarily related to the ionic composition and SAR, but not simply due to EC alone. Similarly, increasing soluble-phase Ca from ionic sources can decrease sodicity indicators, despite having high total soluble salts (Pistocchi et al., 2017).

As more diatomite was applied, WS-Na levels decreased indicating that diatomite altered the soil solution, moving it from an Na dominated liquid to one dominated by other solutes. This is very important for soils that are structurally sensitive. This is because soluble Na ions are responsible for dispersing clay and causing problems with infiltration rates. Decreasing amounts of dissolved Na ions - despite increasing total salinity levels - demonstrate that diatomite modified the quality and not just the quantity of dissolved salts.

The significant pattern of interaction exhibited by WS-K supports the concept of a highly phase dependent and moisture and cation competitive dynamic in regards to K. This reinforces previous interpretations that amending soils has no separate effect for each type of ion; it alters the overall ionic equilibrium of the soil solution.

The WS-HCO_3 and WS-Cl levels were found to decrease with the addition of diatomite, whereas the levels of WS-SO_4 experienced an increase, especially at the DT30FC60 treatment level. This shows that the addition of diatomite also influenced the anionic composition of the soil solution as well as the cation concentration. The decrease in bicarbonate may be the result of changes in carbonate equilibrium and the relationship between Ca and Mg, while the increase in SO_4 may stem from a higher concentration of ions and decreased leaching. Evidence from previous research (Tanji, 2002) indicates that the principal soluble salts in saline environments are typically comprised of sulfates and chlorides of Na, Ca, and Mg and can vary significantly depending on the moisture regime of the soil and exchange of ions (via cation-anion exchange). This work indicates that diatomite may have impacted both total salinity and quality of dissolved ion environment.

4.5. Role of Soil Moisture Regimes in Regulating Diatomite Effects

A striking feature of the present dataset was that many of the strongest treatment responses occurred under FC60 rather than under the highest soil moisture regimes (FC100) or severe water deficit (FC40). This indicates that soil moisture regimes was a major regulator of how diatomite interacted with the soil system.

The relationship between soil moisture and ion chemistry can determine if salts are diluted, concentrated, or redistributed in the root zone; the moisture regime of soil at FC serves as a reference for ion dissolution potential (i.e., potential for ions to dissolve into solution with the presence of water). At FC100, while high levels of ion dissolution can occur, high rates of water flow can also increase the downward movement of ions and decrease the amount of time ions remain in the root zone. Conversely, under severe water deficits, the lack of continuity of soil water may restrict dissolution, diffusion, and exchange. On the other hand, moisture levels at FC60 appear to provide a more optimal balance between moisture levels sufficient for ions to be released, exchanged, and redistributed vs. moisture levels low enough to minimize excessive leaching. Similar interpretations of salinity and irrigation studies support this, where intermediate deficits produce the maximum amount of measurable change in the concentration of ions present and the composition of soil solution (Corwin and Lesch, 2005; Letey, 2000). According to Stavi et al. (2021) interaction of moisture regime and ion chemistry is an important controlling factor on whether salts will be diluted, concentrated or redistributed within the root zone. Thus, the repeated occurrence of pronounced DT × SMR interactions under FC60 likely reflects an optimal balance between solute mobility and solute retention. From a practical perspective, this suggests that the effectiveness of diatomite as a soil amendment cannot be interpreted independently of irrigation management.

4.6. Evaluation of Soil Chemical Properties and Ionic Relationships by Pearson Correlation Analysis

The Pearson correlation matrix revealed strong and systematic relationships among soil chemical properties, exchangeable cations, water-soluble ions, and available nutrients under diatomite application and different soil moisture regimes (Figure 1).

There were high degree of positive relationships exist between WS-Ca, WS-Mg, and WS-$S0_4$. EC and salt content indicates that soil salting is mainly caused by accumulation of divalent cations (i.e., Ca^{2+}, Mg^{2+}), as well as sulphate ions in soil solution. This result agrees with former research indicating that salinisation process and salinity in calcareous, semi-arid soil systems are dominated by Ca^{2+}, Mg^{2+}, and SO_4^{2-} ions, and not only by Na^{+} in condition of adequate water (Tanji, 2002; Stavi et al., 2021).

Exchangeable Na and SAR both have a strong correlation with WS-Na. In contrast, WS-Na had a weak or negative correlation with EC and drinking-water soluble Ca and Mg (divalent cations). Therefore, Na in the soil is tied more to sodicity than to overall salinity. The fact that WS-Na exhibits such a strong relationship with Na and SAR supports the general consensus that sodicity is primarily determined by Na dominance (Qadir and Oster, 2004; Pistocchi et al., 2017) in both the solution and exchange complex of soils.

There was a strong negative relationship between exchangeable Ca and Na as well as between exchangeable Ca and SAR. This indicates that Ca is an important factor in the displacement of Na from exchange sites, thereby reducing the risk of sodicity. This inverse relationship has been documented in studies looking at soil amendments and reclamation, where Ca-rich materials significantly help with the displacement of Na from soils and improve soil structural stability (Stavi et al., 2021).

WS-Ca and Mg exhibited a strong positive relationship with EC, but a negative relationship with exchangeable Na and SAR. Therefore, the addition of divalent cations to a soil solution reduces sodicity while increasing the total amount of salts within the soil solution. The documented examples of this occurrence in saline-sodic or salinity/sodicity type systems are

when Ca^{2+} and Mg^{2+} are acting as flocculating agents that counteract the dispersive nature of Na (Pistocchi et al., 2017).

The values of available Ca and Mg are confirmed through strong correlations with one another indicating the two nutrients have a co-dependent function in soil. While both parameters were correlated negatively to EC and water-soluble ions, indicating increasing salinity and solution phase ion concentrations will reduce their availability (possibly their extractability). This finding implies that nutrients' availability is not only a function of total concentration, but also includes considerations of the phases available to plants and the equilibrium of soil solution to a greater extent than just the total amount of a nutrient (Bel et al., 2020).

The P_2O_5 that was made available had medium positive correlations with the EC of the soils and water-soluble ions, which would suggest a possibly moderate increase in ionic strength may enhance P availability by the processes of desorption or reduction of P fixation under some condition. Hinsinger (2001) and Lindsay (1979) identify that P availability in calcareous soils is affected considerably by the chemical environment and water content of the soil.

K exhibited a distinct behavior compared to other cations. Available K_2O and exchangeable K showed weak or negative correlations with EC and divalent cations, while WS-K displayed moderate positive correlations with EC and salinity parameters. This suggests that K distribution among soil fractions was strongly influenced by cation competition and ionic strength, which is consistent with the findings of Jalali (2008), who reported that K dynamics are highly sensitive to interactions with Ca, Mg, and Na.

Compared to the other cations, K had noticeably different behavior. The available K content as K_2O and exchangeable K were poorly or negatively correlated with EC and the divalent cations in this study, whereas WS-K was moderately positively correlated with both EC and salinity parameters. The findings suggest that K distribution in soil is greatly affected by cation competition and ionic strength, which supports the findings of Jalali (2008) that K dynamics are strongly influenced by the interactions of Ca, Mg and Na.

Although soil pH did have some weak correlations with other parameters, they were all low enough that they confirmed that the pH of the soils was extremely stable and buffered because of the presence of $CaCO_3$. This limited variability of pH corroborates the buffering characteristics of calcareous soils (Lindsay, 1979; Sparks, 2003).

Overall, the correlation matrix clearly demonstrates that diatomite application and soil moisture regimes induced coordinated changes in soil chemical properties, particularly by enhancing the role of Ca and Mg in the soil solution while reducing Na dominance. This indicates that the system shifted from a Na-dominated condition toward a more Ca–Mg - regulated ionic balance, which is generally associated with improved soil structural and chemical stability.

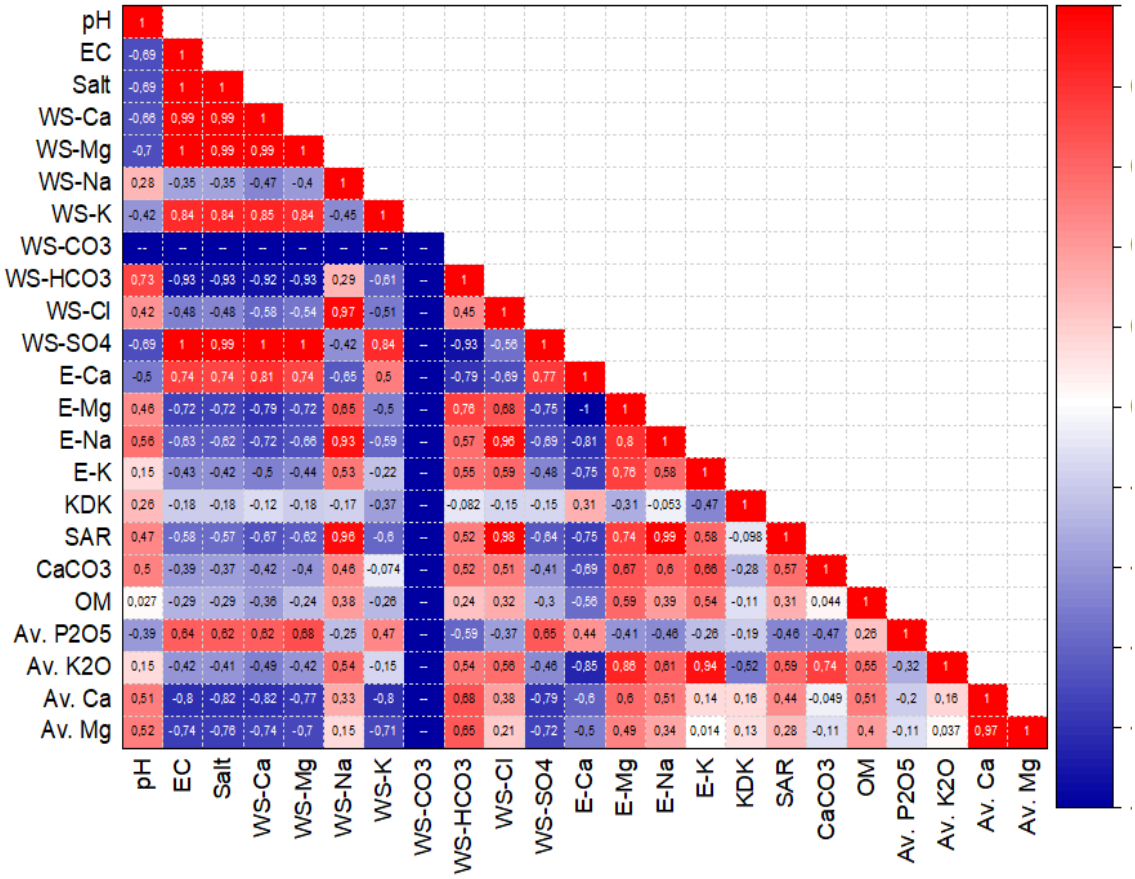


Figure 1. Pearson correlation matrix illustrating the relationships among soil chemical properties, exchangeable cations, water-soluble ions, and available nutrients under diatomite application and soil moisture regimes

5. Conclusion

Diatomite application significantly modified soil chemical properties, ionic composition, and sodicity-related indicators under different soil moisture regimes in a calcareous–slightly alkaline soil. However, its effects were not uniformly beneficial or detrimental; rather, diatomite acted through a multidimensional mechanism involving ion redistribution among soil fractions, modification of soil solution composition, and strong interaction with irrigation-driven water dynamics. Overall, increasing diatomite dose generally increased EC, salt content, CEC, exchangeable Ca, and WS-Ca, WS-Mg, and WS-SO_4, while reducing exchangeable Na, WS-Na, and SAR. The results of this investigation show that diatomite increases the concentration of total soluble salts in soils; but at the same time creates a more favourable ratio of Ca to Mg ions and lowers the sodicity stress on soils. The response of nutrient-related parameters was quite variable, indicating that the impact of diatomite has more to do with changing soil chemical equilibria and ion partitioning than it does with simply improving nutrient availability. FC60 had the greatest impacts among all soil moisture regimes tested, indicating that conditions created by moderate moisture deficits will enhance the impact of diatomite. Therefore, it can be concluded that diatomite's beneficial agronomic and ameliorative properties are significantly influence by application rate and moisture regime. Diatomite can be used as a mineral amendment for ameliorating sodic-induced chemical conditions in calcareous-slightly alkaline soils with an ionic imbalance. The increases in salinity-related parameters indicate that the effects should be evaluated at the field level in terms of their practical suitability for use with crops and the long term effects on the soil.

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DOES EDUCATİON REDUCE GENDER INEQUALİTY İN THE LABOUR MARKET? EVİDENCE FROM SOUTHEAST EUROPE

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ABSTRACT

This paper looks at how education relates to gender differences in the labour market in a group of Southeast European countries over the period 2010–2023. The main goal is to understand whether higher public spending on education is linked to smaller gaps in unemployment between women and men. The analysis uses panel data drawn from the World Bank and Eurostat. Gender inequality is captured through the difference in unemployment rates, while the empirical approach relies on a fixed effects framework, supported by descriptive patterns and simple visual exploration of the data.

The results show clear differences across countries, both in terms of levels and how these gaps change over time. There is no single pattern shared by all countries. The link between education spending and the unemployment gap appears limited, and the estimates do not provide strong statistical support for a direct effect. At the same time, general economic conditions seem to matter more, pointing to the importance of factors beyond education.

The findings suggest that improving education funding on its own is unlikely to close gender gaps in the labour market. Progress depends on a broader set of actions that tackle barriers women face in employment. By focusing on a regional setting that is not often covered in detail, this study adds grounded evidence to the discussion on gender inequality and economic development.

Keywords: education; gender inequality; labour market; unemployment gap; economic conditions, public policy; Southeast Europe

1. Introduction

In recent decades, education has taken a central place in discussions on gender equality and economic development, often viewed as a key channel for improving opportunities in the labour market (Becker, 1964; Sen, 1999). Expanding women's access to education, in particular, has frequently been associated with greater economic participation and improved labour market outcomes (Psacharopoulos & Patrinos, 2018). Yet empirical evidence suggests that this link is neither automatic nor uniform across contexts.

Across many countries, including those in Southeast Europe, improvements in women's educational attainment have not always been accompanied by consistent reductions in gender disparities in the labour market. Even where participation in education has expanded considerably, gaps in unemployment and access to employment opportunities remain visible. This trend points to the influence of additional factors, including labour market structures, institutional arrangements, and persistent social norms (Klasen & Lamanna, 2009; Blau & Kahn, 2017).

Against this background, this analysis contributes to the ongoing debate by examining how education is associated with gender inequality in the labour market across a group of Southeast European countries over the period 2010–2023. Rather than assuming a direct effect of education, the analysis evaluates this association within a broader economic and institutional setting, where multiple forces shape labour market outcomes.

The empirical evidence presented here indicates that gender inequality in the labour market is characterised by considerable heterogeneity across countries and over time. Descriptive patterns and graphical analysis do not point to a strong link between education expenditure and reductions in gender disparities. This pattern is consistent with the fixed effects estimates, where the coefficient for education spending does not reach statistical relevance.

By contrast, economic development appears more closely connected to gender disparities, suggesting that structural transformation and labour market organisation play a central role (Goldin, 2014; Stiglitz, 2012). This shifts the focus away from viewing education as a standalone solution and towards a broader perspective that considers the interaction between education, economic structures, and institutional settings.

The main contribution of this analysis lies in providing empirical evidence from a regional context that remains relatively underexplored, while also drawing attention to the limits of approaches that rely exclusively on education as a tool for achieving gender equality. Instead, it supports a more integrated perspective that accounts for structural and institutional constraints shaping labour market outcomes.

The remainder of the study is structured as follows. Section 2 reviews the relevant literature, Section 3 describes the data and methodology, Section 4 presents the empirical results, and the final sections discuss implications and conclude.

2. Literature Review

2.1 Education as a mechanism for women's empowerment

In economic and social research, education is often treated as one of the most durable channels for expanding individual opportunities and improving women's position in society (Becker, 1964; Sen, 1999). From this perspective, higher levels of education are not only linked

to economic returns but also to broader shifts in decision-making, agency, and interaction with institutions. Education tends to increase women's participation in economic life, strengthen their autonomy, and indirectly reshape family and social structures (Boserup, 1970; Psacharopoulos & Patrinos, 2018).

Education does not linearly translate into empowerment. In many contexts, even when women achieve higher levels of education, labour market outcomes remain constrained. This suggests that education creates potential but does not guarantee its translation into tangible outcomes. As a result, part of the literature treats education as a necessary, but not sufficient, condition for achieving gender equality (Klasen & Lamanna, 2009).

2.2 Gender Inequality in the Labour Market

Research on labour markets shows that gender disparities emerge across multiple dimensions at once, including participation, employment, wages, and opportunities for career advancement (Blau & Kahn, 2017; Goldin, 2014). Even in economies where educational gaps have narrowed considerably, these differences remain visible.

Part of the explanation lies in the sectoral structure of the economy, where women are more frequently concentrated in lower-paid or less stable sectors. Another factor relates to career interruptions, often associated with family responsibilities and childcare. Social norms and cultural expectations also shape how women's participation in the labour market is organised (Esping-Andersen, 1990; Stiglitz, 2012).

This body of work suggests that gender inequality does not stem from a single source, but rather from the interaction of economic, institutional, and social elements. Within this broader setting, the role of education needs to be interpreted as part of a wider system rather than as an isolated factor.

2.3 Education and the Reduction of Gender Inequality

A substantial part of the literature addresses whether education contributes to narrowing gender disparities in the labour market (Psacharopoulos & Patrinos, 2018; Klasen & Lamanna, 2009). Some contributions show that higher levels of female education are associated with greater labour market participation and improved employment prospects. From this perspective, education enhances individual competitiveness and lowers entry barriers.

The evidence, however, is not uniform. In several cases, gender gaps persist even among individuals with comparable levels of education. This points to the limits of education as a standalone mechanism for reducing inequality. Factors such as discrimination, labour market structures, and public policy frameworks play a central role in shaping how economic opportunities are distributed (Blau & Kahn, 2017).

2.4 The Southeast European Context

In Southeast European countries, the connection of education with labour market outcomes reflects a distinct form of complexity. These economies have undergone rapid structural transformation, reshaping employment patterns and introducing new forms of labour market uncertainty (European Commission, 2020; World Bank, 2024). Despite rising participation in education, women's integration into the labour market remains relatively limited when compared to broader European benchmarks.

An important feature of the region lies in the gap between formal alignment with international standards and the slower pace of change in practice. Reform processes often prioritise institutional convergence, while adjustments in labour market structures take longer to materialise. As a result, education may improve qualifications without immediately altering access to employment opportunities or the underlying structure of the labour market.

2.5 Research Gap

Although a substantial body of work exists on education and gender inequality, these two dimensions are often examined separately. On one side, research tends to focus on access to and expansion of education; on the other, labour market studies concentrate on economic outcomes (Becker, 1993; Mincer, 1974). Less attention has been given to how these processes operate jointly in practice, particularly in transition economies (Kabeer, 2012; World Bank, 2012).

This research addresses this gap by directly linking education to gender disparities in the labour market within a specific regional setting. Focusing on Southeast Europe, the analysis aims to provide a more nuanced understanding of the conditions under which education may contribute to reducing gender inequality, especially in contexts shaped by institutional transformation and labour market restructuring (Klasen & Lamanna, 2009; European Commission, 2020).

3. Data and Methodology

3.1 Data sources and empirical scope

The empirical analysis relies on harmonised secondary data obtained from the World Bank (World Development Indicators) and Eurostat, which ensure comparability across countries and over time (World Bank, 2024; Eurostat, 2024). The period under consideration spans 2010–2023, capturing a phase marked by notable economic and institutional changes across the region.

The focus is placed on a group of Southeast European and Western Balkan countries: Albania, Greece, Romania, Bulgaria, Serbia, North Macedonia, Montenegro, and Bosnia and Herzegovina. Including these countries allows for a comparative perspective across economies with different levels of development and distinct labour market structures, while still sharing common historical and institutional features.

3.2 Variables and Measurement

The analysis incorporates a set of key indicators related to education and labour market outcomes.

Public expenditure on education, measured as a percentage of GDP, is used as a proxy for government commitment to the education sector.

Unemployment rates are considered separately for women and men. Based on these two indicators, the main dependent variable is constructed as the gender gap in the labour market, defined as the difference in unemployment rates across genders:

Gender gap = female unemployment rate − male unemployment rate

This measure captures disparities in access to employment and serves as an indicator of gender inequality in the labour market.

GDP per capita is included as a proxy for the level of economic development, while inflation is used to account for broader macroeconomic conditions that may influence labour market outcomes.

3.3 Empirical Approach

The analysis follows a combined approach, integrating descriptive and econometric techniques.

a) Descriptive analysis

The first stage presents the main trends of the variables through tables and figures. This step allows for the identification of general patterns and cross-country differences in labour market outcomes and education indicators.

b) Econometric analysis (panel data)

To assess how education is associated with gender inequality in the labour market, a fixed effects panel model is employed. This framework accounts for variation across countries and over time, while controlling for unobserved heterogeneity.

The baseline specification can be expressed as:

$$\text{GenderGap}_{it} = \alpha + \beta_1 \text{EduExp}_{it} + \beta_2 \text{GDPpc}_{it} + \beta_3 \text{Inflation}_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where:

- i denotes the country
- t denotes time
- μ_i captures country fixed effects
- λ_t captures time fixed effects

This specification controls for time-invariant country characteristics and common shocks affecting all countries in a given period.

3.4 Methodological Rationale

The choice of a fixed effects specification is grounded in the assumption that countries differ in persistent ways with respect to institutional structures, social norms, and labour market characteristics. By accounting for these time-invariant differences, the analysis focuses on within-country variation over time, allowing for a more accurate assessment of how changes in key variables are associated with changes in gender inequality (Wooldridge, 2010; Baltagi, 2021).

This specification is particularly suitable in a cross-country setting, where unobserved heterogeneity may bias the estimates if not properly controlled. Fixed effects estimation addresses this issue by removing country-specific effects that remain constant over time (Hsiao, 2014).

The inclusion of macroeconomic variables such as GDP per capita and inflation helps isolate the role of education from broader economic conditions that may influence labour market outcomes. These controls capture variations in economic development and macroeconomic stability, which are often linked to employment dynamics and gender disparities (Stock & Watson, 2020).

The use of panel data allows for a richer empirical framework by combining cross-sectional and time-series dimensions, improving the ability to detect underlying patterns that would not be observable in a purely cross-sectional setting (Baltagi, 2021).

3.5 Methodological Limitations

Several limitations should be acknowledged. Measuring gender inequality solely through differences in unemployment does not capture all dimensions of the labour market, such as wage disparities or the quality of employment. The available data may also contain gaps for certain countries or years. The analysis focuses on statistical associations and does not aim to establish causal effects directly.

Despite these limitations, the adopted approach provides a consistent basis for assessing whether, and to what extent, education is linked to changes in gender inequality in the labour market.

4. Empirical Results

4.1 Descriptive Statistics

Table 1 reports the descriptive statistics for the main variables included in the analysis.

Table 1. Descriptive Statistics (2010–2023, N = 59 country–year observations)

Variable	N	Mean	Std. Dev.	Min	Max
Gender gap	59	0.95	3.27	-4.38	8.79
Education expenditure (% GDP)	59	3.49	0.46	2.73	4.71

GDP per capita (constant USD)	59	7,955.04	3,974.04	3,677.89	20,552.32
Inflation (%)	59	3.37	3.96	-1.74	15.33

Notes: Descriptive statistics are based on panel data covering Albania, Greece, Romania, Bulgaria, Serbia, North Macedonia, Montenegro, and Bosnia and Herzegovina over the period 2010–2023.
The gender gap is calculated as the difference between female and male unemployment rates. GDP per capita is expressed in constant US dollars.

As shown in Table 1, the gender gap in unemployment is positive on average, indicating higher unemployment among women compared to men across the countries considered. The relatively large variation and the presence of negative values indicate that this gap is not uniform and varies across countries and over time.

Education expenditure appears relatively stable, whereas GDP per capita shows considerable variation, reflecting differences in economic development across the region. Inflation also exhibits noticeable fluctuations, pointing to changing macroeconomic conditions during the period under consideration.

The descriptive statistics point to a heterogeneous economic and institutional environment, within which the role of education in shaping gender inequality may differ across contexts.

4.2 Correlation Analysis

Table 2 presents the pairwise correlations among the main variables included in the analysis.

Table 2. Correlation Matrix

Variable	**Gender gap**	**Education expenditure**	**GDP per capita**	**Inflation**
Gender gap	1.000	0.040	0.439	-0.124
Education expenditure	0.040	1.000	0.052	-0.031
GDP per capita	0.439	0.052	1.000	0.098
Inflation	-0.124	-0.031	0.098	1.000

Notes: The table reports pairwise correlation coefficients between the main variables. Values range between -1 and 1, where positive values indicate a direct relationship and negative values indicate an inverse relationship.

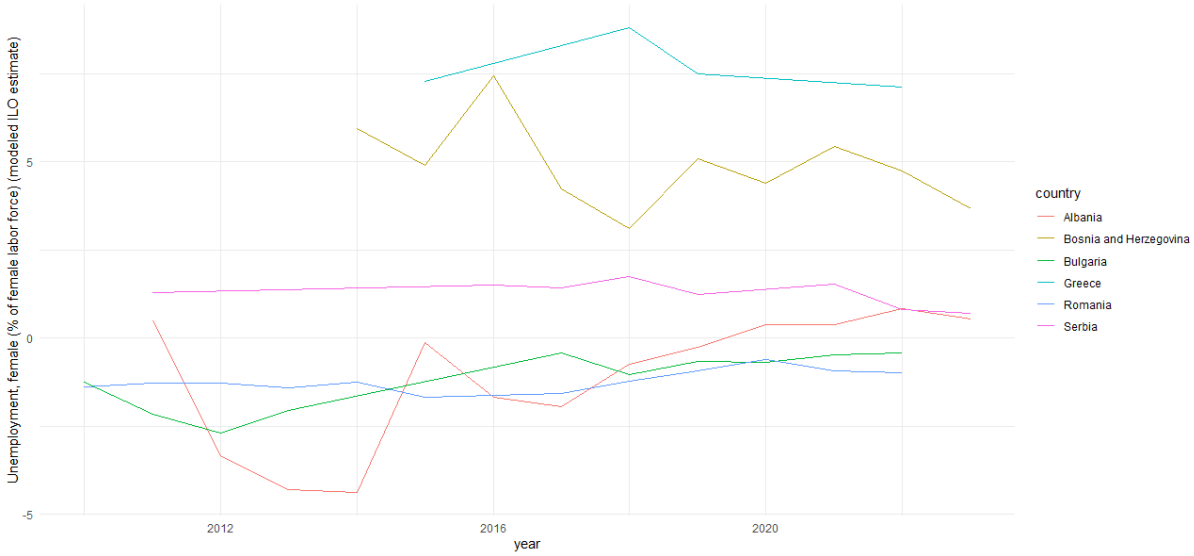
The results indicate that the correlation of education expenditure with gender inequality is very weak, suggesting no clear direct association at the descriptive level. GDP per capita shows a more noticeable connection with gender differences, while inflation does not display a consistent pattern.

These results point to a complex structure across the variables, which cannot be fully understood through simple linear associations. This supports the use of econometric analysis to examine these dynamics in greater detail.

4.3 Dynamics of Gender Inequality Across Countries

Figure 1 illustrates the evolution of the gender gap in unemployment for each country over the period under consideration.

Figure 1. Gender Gap in Unemployment Across Countries (2010–2023)



Notes: The figure illustrates the evolution of the gender gap in unemployment, calculated as the difference between female and male unemployment rates. Positive values indicate higher unemployment among women, while negative values indicate higher unemployment among men. Data are based on World Bank indicators and cover Albania, Bosnia and Herzegovina, Bulgaria, Greece, Romania, and Serbia over the period 2010–2023.

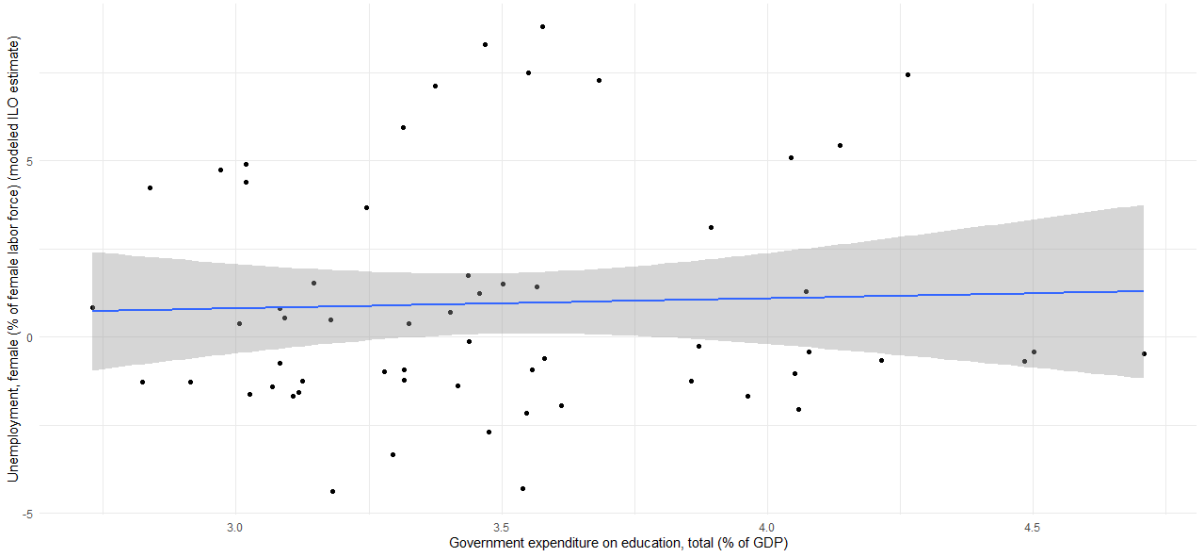
As shown in the figure, gender inequality in the labour market varies markedly across countries and does not follow a uniform trajectory. In some cases, the gap remains consistently positive and relatively high, while in others it narrows or even reverses during certain periods.

This dynamic points to the importance of country-specific factors in shaping gender outcomes, indicating that no single pattern characterises the evolution of inequality across the region.

4.4 Education and Gender Inequality: Descriptive Evidence

Figure 2 illustrates how education expenditure is associated with the gender gap in unemployment.

Figure 2. Education Expenditure and Gender Gap in Unemployment



Notes: The figure presents the relationship between government expenditure on education (as a percentage of GDP) and the gender gap in unemployment. The gender gap is calculated as the difference between female and male unemployment rates. Each point represents a country–year observation. The fitted line represents the linear trend, with the shaded area indicating the 95% confidence interval.

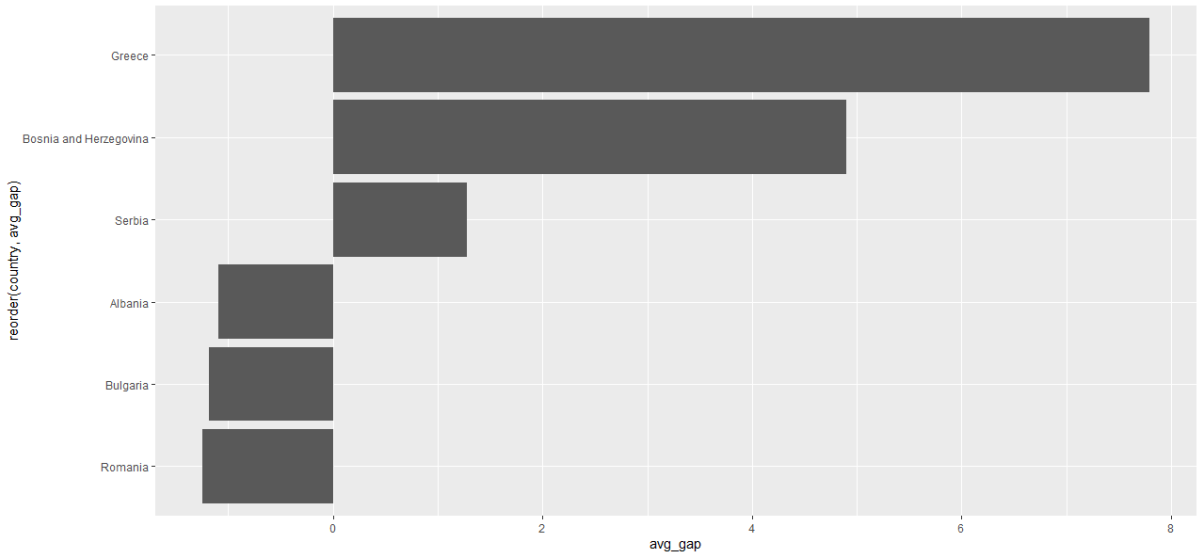
The observations are widely dispersed, indicating a weak association across the two variables. The fitted line shows a slight upward tendency, suggesting that higher levels of education expenditure are not systematically linked to a reduction in gender inequality.

This points to the limited direct influence of education and to the importance of additional factors in shaping labour market outcomes.

4.5 Cross-country Comparison

Figure 3 reports the average gender gap in unemployment for each country.

Figure 3. Average Gender Gap in Unemployment by Country (2010–2023)



Notes: The figure reports the average gender gap in unemployment for each country over the period 2010–2023. The gender gap is defined as the difference between female and male unemployment rates. Positive values indicate higher unemployment among women, while negative values indicate higher unemployment among men.

The results show clear differences across countries. Some cases display relatively high positive values, indicating a persistent disadvantage for women in the labour market, while others exhibit smaller or even negative values.

These differences underline the importance of economic and institutional context in shaping gender inequality and indicate that the role of education may vary considerably across countries (Klasen & Lamanna, 2009; Blau & Kahn, 2017). Structural features of labour markets and country-specific conditions appear to influence how gender disparities evolve over time (Goldin, 2014; European Commission, 2020).

4.6 Panel Model Results

Table 3 reports the results of the fixed effects panel model.

Table 3. Fixed Effects Estimates (Dependent variable: Gender Gap)

Variable	Coefficient	Std. Error	t-value	p-value
Education expenditure (% GDP)	0.304	0.425	0.716	0.478
GDP per capita	0.000324	0.000166	1.953	0.056

Inflation (%)	-0.040	0.045	-0.890	0.378

Model statistics:

- Observations: 59
- Number of countries: 6
- R^2 (within): 0.093
- Adjusted R^2: -0.052
- F-statistic: 1.716 (p = 0.176)

Notes: The table reports fixed effects (within) panel estimates. The dependent variable is the gender gap in unemployment (female minus male unemployment rate). Country fixed effects are included. Standard errors are robust to heteroskedasticity. Significance levels: *** p < 0.01, ** p < 0.05, * p < 0.1.

The coefficient on education expenditure is not statistically relevant, indicating that changes in education spending are not consistently associated with reductions in gender inequality in the labour market. Economic development shows a more noticeable connection, while inflation does not emerge as a relevant factor.

The results indicate that education does not act as a standalone driver of gender inequality, and that broader economic and institutional factors shape how these outcomes evolve.

5. Discussion

The role of education in shaping gender inequality in the labour market appears more complex than often assumed in policy debates. While education is widely viewed as a key channel for women's empowerment, the empirical evidence presented here shows that higher investment in education is not consistently associated with reductions in gender differences in unemployment.

A central observation is the absence of a strong association of education expenditure with gender inequality, both in the descriptive analysis and in the panel model. This suggests that education, although important, does not operate as a sufficient mechanism for addressing gender disparities in the labour market. Its influence appears to depend on broader economic structures and labour market organization (Klasen & Lamanna, 2009; Blau & Kahn, 2017).

One possible explanation relates to sectoral allocation of employment. In many of the countries considered, women remain concentrated in sectors with lower productivity or more limited stability, which constrains the returns associated with higher educational attainment. Education may enhance individual skills, yet it does not automatically alter how opportunities are distributed across the labour market (Goldin, 2014).

Another relevant dimension concerns social and institutional norms. Even where women achieve similar or higher levels of education, informal barriers and cultural expectations may limit their full participation in economic activity. This is particularly evident in contexts where traditional gender roles remain influential (Seguino, 2010; European Commission, 2020).

A more visible role emerges for economic development. The observed connection of GDP per capita with gender differences suggests that broader structural transformations—such as sectoral diversification and increased demand for skilled labour—may create more favourable conditions for narrowing disparities (Dollar & Gatti, 1999; World Bank, 2012).

Cross-country variation further supports this interpretation. As illustrated in the figures, some countries display persistently high gender differences, while others show more balanced outcomes or temporary reversals. These contrasts indicate that national policies and institutional arrangements play a decisive role in shaping labour market outcomes.

From a policy perspective, several implications emerge. Increasing education expenditure alone is unlikely to reduce gender inequality in the absence of complementary measures. Policies need to address structural barriers that limit women's participation in the labour market.

A more integrated approach is required, linking education policy with employment measures, childcare support, flexible work arrangements, and anti-discrimination frameworks. Without such interventions, the potential of education to contribute to gender equality remains constrained.

Reducing gender inequality is closely tied to broader economic and institutional transformation. In this sense, education should be understood as part of a wider development strategy rather than as a standalone solution.

6. Conclusion and Policy Implications

This analysis examined the role of education in shaping gender inequality in the labour market, focusing on a group of Southeast European countries over the period 2010–2023. By combining descriptive evidence with panel estimation, it assessed whether investment in education is associated with measurable improvements in women's position in the labour market.

Education remains an important component of social and economic development, yet its contribution to reducing gender inequality appears limited and uneven. At the empirical level, no consistent association emerges linking education expenditure to differences in unemployment outcomes. This indicates that education alone does not ensure more balanced labour market outcomes.

A key implication is that gender inequality cannot be understood or addressed through a single policy dimension. Even where women's educational attainment has improved substantially, disparities in labour market outcomes persist, reflecting the influence of structural and institutional factors. Education expands opportunities, but it does not guarantee that these opportunities translate into equal outcomes.

From a policy perspective, a more integrated approach is required. Investment in education needs to be complemented by active labour market policies, measures supporting work–family balance, and interventions addressing discrimination and institutional barriers. Such a combination is necessary for education to contribute more effectively to gender equality.

Economic development and structural transformation also play a central role in shaping gender outcomes. This suggests that progress in gender equality depends not only on sector-specific policies but also on broader development strategies that expand employment opportunities and strengthen economic inclusion.

Several limitations should be considered. Measuring gender inequality solely through differences in unemployment does not capture other important dimensions, such as wage disparities or job quality. The analysis also focuses on empirical associations and does not aim to fully identify causal mechanisms.

Future research could extend this approach by incorporating additional indicators of gender inequality and by exploring more deeply the channels through which education influences labour market outcomes. Greater attention to the interaction of education, institutions, and social policies would contribute to a more comprehensive understanding of these dynamics.

Education remains a central element of development, yet its role in reducing gender inequality depends on the broader economic and institutional context. Achieving more balanced outcomes requires positioning education within a wider strategy aimed at inclusion and equality in the labour market.

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DOES MEDITERRANEAN DIET ADHERENCE ALWAYS MEAN LOWER KITCHEN CARBON FOOTPRINTS? THE ERODING ROLE OF FOOD WASTE AND CONSUMER BEHAVIOUR

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ABSTRACT

The present study evaluates if a lower carbon footprint from food sources, adapted for food waste generation and consumer behavior, is consistently found with adherence to a Mediterranean diet. The Mediterranean diet is a healthful and ecologically friendly model of the diet, as it emphasizes vegetables, fruits, legumes, and grains more than others. While a diet may theoretically be low-carbon, it does not mean that the same diet will deliver similar environmental benefits in practice at household level. The edge this could provide is often diminished through behavioral factors like food waste, unplanned shopping, convenience-oriented consumption and poor kitchen management.

A simplified Turkish food basket was created, based on 2017 Turkey Nutrition and Health Survey data. Emission coefficients for greenhouse gases were assigned to the food groups in this basket of items, and theoretical footprints for carbon dioxide were calculated. The Turkish food basket under observation had a daily per capita carbon footprint of 3,261 kg CO_2-equivalent based on the calculations. Then, two alternative scenarios closer to the Mediterranean diet were developed. The moderate Mediterranean scenario further reduced the carbon footprint by 16.4%, and the strong Mediterranean scheme raised this reduction to 29.7%. This finding indicates that the relatively sharp decline in red meat consumption, specifically, plays a major role in the carbon footprint.

This advantage was found to be reduced, however, when food waste was incorporated into the model. The Mediterranean diet's carbon preferentiality was verified with low, moderate and high waste assumption levels, however at high waste the situation for the moderate Mediterranean scenario was close to that of the current Turkish food basket. Moreover, in comparing the environmental profiles of conscious and planned consumer with convenience-oriented, high-friction consumer profiles, it emerged that identical theoretical food baskets resulted in very different environmental outcomes.

In this context, the study proposes the concept of the Mediterranean Efficiency Gap. This concept expresses the difference between the theoretical carbon advantage of the Mediterranean diet and the actual carbon performance resulting from household-level behavior and waste. In conclusion, the study shows that sustainable diets should be evaluated not only through food composition but also in conjunction with waste, planning, storage, and consumer behavior. Therefore, it is concluded that policies promoting the Mediterranean diet should include interventions to reduce food waste and strengthen kitchen management, in addition to nutrition education.

Keywords: Mediterranean diet, Food waste, Carbon footprint, Consumer behaviour, Sustainable diets, Household food choices

AKDENİZ DİYETİNE BAĞLILIK HER ZAMAN DAHA DÜŞÜK MUTFAK KARBON AYAK İZİ ANLAMINA GELİR Mİ? GIDA İSRAFININ VE TÜKETİCİ DAVRANIŞININ AŞINDIRICI ROLÜ

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ÖZET

Bu çalışma, Akdeniz tipi beslenmeye uyumun her durumda daha düşük mutfak kaynaklı karbon ayak izi üretip üretmediğini, gıda israfı ve tüketici davranışını birlikte dikkate alarak incelemektedir. Akdeniz diyeti genellikle sebze, meyve, baklagil ve tahıl ağırlıklı yapısı ile daha sağlıklı ve çevresel açıdan daha sürdürülebilir bir beslenme modeli olarak değerlendirilmektedir. Ancak bir diyetin teorik olarak düşük karbonlu olması, hanehalkı düzeyinde gerçek uygulamada da aynı düzeyde çevresel avantaj sağlayacağı anlamına gelmemektedir. Özellikle gıda israfı, plansız alışveriş, kolaylık odaklı tüketim ve zayıf mutfak yönetimi gibi davranışsal unsurlar, bu avantajı önemli ölçüde azaltabilmektedir.

Çalışmada, Türkiye Beslenme ve Sağlık Araştırması 2017 verileri temel alınarak sadeleştirilmiş bir Türkiye beslenme sepeti oluşturulmuş, bu sepette yer alan gıda gruplarına sera gazı emisyon katsayıları atanarak teorik karbon ayak izi hesaplanmıştır. Hesaplamalarda Türkiye'nin gözlenen beslenme sepeti için günlük kişi başı karbon ayak izi 3.261 kg CO_2-eşdeğeri olarak bulunmuştur. Daha sonra Akdeniz tipi beslenmeye daha yakın iki farklı senaryo oluşturulmuştur. Orta düzey Akdeniz iyileştirme senaryosu karbon ayak izini yaklaşık %16.4 azaltırken, güçlü Akdeniz iyileştirme senaryosu bu azalışı yaklaşık %29.7'ye çıkarmıştır. Bu sonuç, özellikle kırmızı et tüketimindeki azalmanın karbon ayak izi üzerinde belirleyici olduğunu göstermektedir.

Ancak modele gıda israfı dahil edildiğinde bu avantajın zayıfladığı görülmüştür. Düşük, orta ve yüksek israf senaryolarında Akdeniz tipi beslenmenin karbon üstünlüğü korunmakla birlikte, yüksek israf düzeylerinde orta düzey Akdeniz senaryosunun neredeyse mevcut Türkiye sepetine yaklaşabildiği ortaya çıkmıştır. Ayrıca çevresel duyarlılığı yüksek ve planlı tüketici profilleri ile kolaylık odaklı, yüksek sürtünmeli tüketici profilleri karşılaştırıldığında, aynı teorik beslenme sepetinin çok farklı çevresel sonuçlar üretebildiği belirlenmiştir.

Bu çerçevede çalışma, Akdeniz Etkinlik Açığı kavramını önermektedir. Bu kavram, Akdeniz tipi beslenmenin teorik karbon avantajı ile hanehalkı düzeyinde davranış ve israf sonrasında ortaya çıkan gerçek karbon performansı arasındaki farkı ifade etmektedir. Sonuç olarak çalışma, sürdürülebilir diyetlerin yalnızca besin kompozisyonu üzerinden değil, aynı zamanda israf, planlama, saklama ve tüketici davranışları ile birlikte değerlendirilmesi gerektiğini göstermektedir. Bu nedenle, Akdeniz tipi beslenmeyi teşvik eden politikaların, beslenme eğitiminin yanında gıda israfını azaltıcı ve mutfak yönetimini güçlendirici müdahaleleri de içermesi gerektiği sonucuna ulaşılmaktadır.

Anahtar Kelimeler: Akdeniz diyeti, Gıda israfı, Karbon ayak izi, Tüketici davranışı, Sürdürülebilir diyetler, Hanehalkı gıda tercihleri

1. Introduction

Dietary sustainability has become a central issue in the broader debate on climate change, public health, and food-system transformation. Recent literature increasingly treats diets not merely as nutritional patterns but as bundles of environmental consequences linked to greenhouse gas emissions, land use, water use, and food-system efficiency (Bôto et al., 2022; Lorca-Camara et al., 2024). In this context, the Mediterranean diet has gained considerable attention as it offers an alternative to Western-style dietary patterns that is associated with high nutritional quality and a reasonably lower environmental impact. Lorca-Camara et al. (2024) conducted a systematic review encompassing the concept of sustainability in food systems and revealed that the Mediterranean diet was identified as one of sustainable dietary patterns in comparative studies against other diets, and reported greenhouse gas footprints ranged approximately from 1.03 to 5.08 kg carbon dioxide equivalent (CO_2-eq) per person per day within included studies. A similar systematic review concluded that the Mediterranean diet exceeds its Western counterparts with regard to environmental burdens by many measures, whilst also performing well nutritionally (Boto et al., 2022).

But this seemingly sustainable advantage has a dark twist. Most studies of dietary sustainability focus on the contents of the plate and far fewer examine what happens to food after it enters the house. Food is chosen, but also stored and portioned, forgotten and re-used, over-bought and discarded. Indeed, household food waste and consumption habits are what ultimately determine the environmental impact of diets. According to UNEP (2024), in 2022, households produced around 631 million tonnes of food waste, equivalent to around 79 kg per capita globally. That means even diets constructed around the food groups that are lower in carbon parts could lose some of their environmental edge when rates of waste are high.

Recent behavioural research supports this point. Boulet et al. (2021) argue that household food waste should be understood within a multi-level behavioural framework and not solely through the lens of isolated demographic predictors. Vittuari et al. (2023) similarly demonstrate the evidence-based reduction of household food-waste that can benefit from greater disaggregation on habitual behaviour and measurement consistency. Food selection is influenced not only by environmental concern (i.e., veganism versus meat consumption) but also other features such as price, the ability to purchase locally or in-season products, product taste and nutritional value (OECD, 2025), which draws on data from a nine-country survey of the Organisation for Economic Co-operation and Development (OECD). Collectively, these studies suggest dietary sustainability is a function of behavioural frictions within the home and not a deterministic outcome of its nutritional archetype.

Previous literature also suggests that food waste is not necessarily lower among people who think they are eating healthy or smart diets. Iori et al. (2022) compared food waste habits across eight countries and found that certain smart-diet consumers reported meaningful levels of food waste, while low food waste was often correlated with time availability, kitchen skills, and better handling of leftovers. This is critical in the context of Mediterranean-style diets, as the diet is characterised by fresh and perishable products (e.g., fruits, vegetables, and minimally processed foods) that are widely used in this dietary pattern, increasing the risk of spoilage when household management practices are ineffective (Iori et al., 2022).

The present study poses a sharper question against this background: Is stricter observance of Mediterranean dietary patterns invariably associated with lower kitchen-related carbon footprints when accounting for food waste and consumer behaviour? The study answers this

question by developing an integrated secondary-data framework of dietary intake structure, food-group emission coefficients, household food-waste scenarios and behaviour-based adjustment factors. Its main argument is that the Mediterranean diet is not automatically low-carbon, but rather that it can be described as a behaviour-contingent sustainability pattern whose realised environmental performance largely depends on how households purchase, manage and dispose of food. This redirection enables the paper's central analytical contribution: the Mediterranean Efficiency Gap, that is, the difference between a theoretical carbon performance of a food basket with a Mediterranean orientation and its behaviour-modified carbon expression.

2. Literature Background

Since 2015, the literature has been strongly in favor of Mediterranean-style diets performing better environmentally than those that are more meat-intensive. Galli et al. (2017) demonstrated that food consumption patterns in Mediterranean countries generate substantial ecological pressure while also revealing pathways amenable to reductions of those pressures through changes in sourcing and dietary composition. More recently, Bôto et al. (2022) and Lorca-Camara et al. (2024) synthesized the evidence and confirmed that, for the most part, environmental impacts of Mediterranean diets were lower than those associated with Western diets across greenhouse gases and a number of other ecological indicators. Álvarez-Álvarez et al. (2024) additionally found that greater adherence to a Mediterranean dietary pattern was associated with lower environmental impact in several dimensions and improvement in adherences reduced greenhouse-gas emissions over time.

Not all low-carbon dietary pathways, however, necessitate completely eliminating animal-based products. Cavaliere et al. (2023), who focused on Italy, demonstrated that food systems can provide substantial reductions in diet-related environmental impact whilst retaining nutritional adequacy, cultural acceptability and affordability. This is methodologically relevant, as it justifies modelling the Mediterranean diets as attainable transitional patterns instead of idealised vegan standards.

If we consider the food-waste literature to date since 2015, it tends to focus on household waste as a sub-problem of disposal, with behaviours treated as an outcome rather than a driver. Boulet et al. (2021) proposed a multilevel framework for household food waste, noting that food waste is influenced by routines, social norms, planning and provisioning practices, and context in households. Vittuari et al. (2023) consolidated household-level waste-reduction research and urged the need for more standardised methods and stronger evidence of behaviour change. Deliberador et al. (2023) mapped 190 household food-waste studies and found that there is a wide range of predictors of behaviour, going further than the traditional Theory of Planned Behavior. Jansson-Boyd et al. (2024) found that adaptive behaviours, emotional engagement and reflection all featured as salient drivers in waste reduction.

The link between dietary pattern and food waste is particularly fascinating. Iori et al. (2022) also had found that dietary patterns related to fresh or smart consumption did not always correlate with less household food waste. In some countries, smart diets were correlated with more wasted calories than others, while lower waste was more closely tied to the time spent preparing food and kitchen management skills as well as shopping lists and leftover use. This indicates that a nutritionally or ethically appealing diet may be poorly performing environmentally if household management is weak.

The OECD's recent efforts bring a useful cross-country behavioural lens. Based on the 2022 EPIC survey, OECD (2025) analysed food choices in nine countries and illustrated how income, household characteristics, environmental attitudes and preferences for local, in-season or minimally packaged food all help to shape consumption behaviour. Importantly, consumers don't pick food for environmental reasons alone. Taste, price, convenience and perceived healthy value and nutritional quality frequently trump ingredients of greater healthiness. This is important because a household may theoretically endorse sustainable consumption without changing its habitual decision-making, which could lead to the low-effort decisions reinforcing wasteful outcomes or patterns of carbon-intensive consumption.

In a related direction, Metin et al. (2024) found that climate-change awareness had a significant positive relationship with healthy and sustainable eating behaviours and with adherence to the Mediterranean diet. This supports the idea that awareness and values may strengthen sustainable dietary adoption, but it does not guarantee low waste or high kitchen efficiency. The behavioural chain is longer than the attitudinal spark.

3. Research Aim and Hypotheses

This study aims to evaluate whether the theoretical low-carbon advantage of Mediterranean diet adherence is preserved once household food waste and consumer behaviour are introduced into the analysis. The study tests the following hypotheses:

H1. Greater adherence to a Mediterranean-style dietary basket is associated with a lower theoretical kitchen-related carbon footprint.

H2. Household food waste weakens the carbon-reducing effect of Mediterranean diet adherence.

H3. Convenience-oriented and price-sensitive behavioural profiles increase the adjusted carbon footprint of Mediterranean-style food baskets.

H4. Preferences for local and in-season foods reduce the adjusted kitchen-related carbon footprint.

H5. The difference between theoretical and adjusted carbon performance, termed the Mediterranean Efficiency Gap, is larger under high-waste and behaviourally inconsistent household scenarios.

These hypotheses are consistent with the environmental literature on Mediterranean diets and with the behavioural literature on household food waste and food choice (Álvarez-Álvarez et al., 2024; Boulet et al., 2021; Iori et al., 2022; OECD, 2025).

4. Data and Methodology

The paper adopts an integrated secondary-data scenario design. This is appropriate because no single available dataset provides, for the same Turkish sample, detailed dietary structure, direct carbon coefficients, household-level food waste, and behavioural choice profiles in one harmonised microdata environment. Instead, the study combines four complementary sources into a single analytical framework:

- Turkey Nutrition and Health Survey 2017 (TBSA 2017) for dietary structure
- Our World in Data food-emissions dataset for greenhouse gas coefficients by food group (Our World in Data -Poore & Nemecek (2018))
- UNEP Food Waste Index Report 2024 for household food-waste benchmarks and scenario construction
- OECD Household Food Choices (2025) plus recent behavioural literature for consumer-profile modifiers

Dietary structure: TBSA 2017 provides the consumption backbone. Its dietary module is based on repeated 24-hour recalls with a 14-day interval, following EFSA-aligned methodology, making it suitable for deriving representative adult dietary baskets by major food groups.

Emission coefficients: Food-group-specific greenhouse gas emission factors are taken from the Our World in Data database based on Poore and Nemecek. These coefficients are expressed in kg CO_2-eq per kg of food product and can be grouped in broad food categories, e.g., red meat, poultry, dairy, legumes, grains (cereals), fruits and vegetables.

Food waste scenarios: global benchmark of household food waste (UNEP, 2024). As the study does not have same sample which is observed in Turkish household wastes quantities, it prefers to use scenario coefficients rather than micro-observations. Three scenarios are proposed:

Low waste: 5% edible household waste

- Medium waste: 10%
- High waste: 20%

These are scenario parameters, not direct UNEP estimates for a single country. They allow sensitivity analysis around the global evidence base.

Behavioural modifiers are built from OECD (2025) and the post-2015 household food-waste literature. Three profiles are proposed:

- Profile A: Environmentally conscious planner

  Higher concern for local and in-season food, stronger planning, lower convenience reliance

- Profile B: Price-sensitive mixed consumer

  Strong affordability focus, moderate planning, moderate waste risk

- Profile C: Convenience-oriented high-friction consumer

  Greater preference for convenience and ready-to-eat options, weaker planning, higher waste risk

These profiles are not claimed as observed Turkish latent classes; they are analytically informed behavioural scenarios.

5. Mathematical Model and Calculation Plan

5.1. The Representative Food Basket (Step 1)

For each food group j, define the average daily quantity consumed:

$$Qj$$

where Qj is expressed in kilograms per person per day.

A Mediterranean adherence score can then be generated using key groups including vegetables, fruits, legumes, cereals/whole grains, fish, olive oil proxy (based on consumption of fats as a whole), red meat and dairy moderation. Where group structure by TBSA is coarse, a simplified Mediterranean Basket Score (MBS) can be adopted:

$$MBSi = k = 1\sum msik$$

where sik is a binary or scaled score for adherence to Mediterranean-consistent intake levels in food group k.

5.2. Compute Theoretical Carbon Footprint (Step 2)

The theoretical diet-related carbon footprint is:

$$CFiT = j = 1\sum nQij \times EFj$$

where:

- CFiT = theoretical carbon footprint of basket i
- Qij = quantity of food group j in basket i
- EFj = emission factor of food group j in kg CO_2-eq/kg

This represents the plate-level theoretical carbon value, pre-waste and behavioural distortions

5.3. Add Food Waste (Step 3)

Let Wi denote the edible food-waste rate for household profile i. Then:

$$CFiW = CFiT \times (1 + Wi)$$

If a household wastes 10% of edible food, its effective carbon burden goes up to theoretically 1.10 times whatever footprint the basket claims it has.

5.4. Add Behavioural Adjustment (Step 4)

Denote Bi the behaviour-related carbon frictions and Si sustainable management strength. Then:

$$\mathrm{CFiA} = \mathrm{CFiT} \times (1 + \mathrm{Wi} + \beta\mathrm{Bi} - \gamma\mathrm{Si})$$

where:

- CFiA = adjusted carbon footprint
- Wi = waste coefficient
- Bi = unsustainable behaviour score
- Si = sustainable behaviour score
- B,γ = behavioural weights

A simple operationalisation could be:

$$\mathrm{Bi} = \mathrm{Ci} + \mathrm{Oi} + \mathrm{P} / 3$$

where:

- Ci = convenience orientation
- Oi = overbuying tendency
- Pi = poor planning intensity

And

$$\mathrm{Si} = \mathrm{Li} + \mathrm{Sei} + \mathrm{Ri} / 3$$

where:

- Li= local purchasing preference
- Sei = seasonal purchasing preference
- Ri = leftover reuse / kitchen management strength

All variables can be normalised to a 0-1 scale.

5.5. Mediterranean Efficiency Gap (Step 5)

The core analytical contribution is:

$$\mathrm{MEGi} = \mathrm{CFiA} - \mathrm{CFiT}$$

where:

- MEGi = Mediterranean Efficiency Gap
- MEGi=0: the household preserves the theoretical sustainability advantage
- MEGi>0: waste and behaviour erode the climate benefit
- Larger MEGi: greater loss of efficiency between dietary intent and household reality

6. Empirical Implementation and Data Construction

6.1. Data Integration Logic

The empirical implementation of the study is based on an integrated secondary-data design. Since no single Turkish microdata source simultaneously provides individual-level dietary intake, food-group greenhouse gas coefficients, household food waste quantities, and consumer-behaviour indicators, the analytical structure combines four complementary sources. Dietary structure is derived from the Turkey Nutrition and Health Survey 2017. Greenhouse gas emission coefficients are assigned using the Our World in Data food-emissions dataset based on Poore and Nemecek. Food-waste adjustment is informed by the UNEP Food Waste Index Report 2024. Behavioural scenario logic is constructed using the OECD Household Food Choices framework and recent household food-waste literature (İlhan et al., 2023; OECD, 2025; UNEP, 2024).

In this section, the first empirical step is to construct a simplified observed Turkish baseline basket for adults using publicly retrievable TNHS/TBSA-based values. The second step is to assign food-group-specific carbon coefficients. The third step is to calculate a theoretical baseline carbon footprint and compare it with the diet-related greenhouse gas estimate reported for Türkiye in the literature. Finally, two modelled Mediterranean-improvement scenarios are created to provide a computational basis for the later food-waste and behaviour-adjusted analysis (İlhan et al., 2023).

6.2. Observed Turkish Baseline Basket

Available TNHS/TBSA-based evidence provides several directly usable anchors for the Turkish adult diet. The TNHS 2017 factsheet reports daily fresh fruit and vegetable consumption at 415 g/day, milk and dairy product consumption at 188 g/day, and red meat plus poultry consumption at 80.5 g/day. A later sustainability analysis using TNHS 2017 further reports that the main staple foods in the national diet were bread at 179.8 g/day and other cereal products at 73.6 g/day. The same study also reports animal-source subgroup quantities of 43.3 g/day red meat, 25.2 g/day poultry, 14.1 g/day eggs, and 14.1 g/day seafood in the Turkish national diet (İlhan et al., 2023). A recent trend analysis based on TNHS data further indicates that 2017 daily intakes were 251.9 g/day for vegetables and 158.9 g/day for fruits, which sum to the 415 g/day figure given in the official factsheet (İlhan et al., 2025 accepted manuscript; Republic of Türkiye Ministry of Health, 2019). Based on these values, the simplified baseline basket used in this study is shown in Table 1.

Table 1. Observed Turkish baseline basket used in the model (g/person/day)

Food group	Quantity (g/day)	Data basis
Bread	179.8	TNHS 2017 national diet
Other cereals	73.6	TNHS 2017 national diet
Vegetables	251.9	TNHS 2017 trend evidence

Fruits	158.9	TNHS 2017 trend evidence
Milk and dairy products	188.0	TBSA/TNHS 2017 factsheet
Red meat	43.3	TNHS 2017 national diet
Poultry	25.2	TNHS 2017 national diet
Eggs	14.1	TNHS 2017 national diet

Source: Prepared by the author.

This basket is intentionally parsimonious. Seafood is reported in the source data, but because of the very wide dispersion of seafood-specific carbon coefficients across production systems and species, seafood is not included in the first validation calculation below. It will be incorporated later as a sensitivity extension if needed. This choice keeps the baseline estimation transparent and avoids introducing unnecessary noise at the first modelling stage (İlhan et al., 2023).

6.3. Greenhouse Gas Coefficients Assigned To Food Groups

To convert food quantities into carbon values, food-group-specific greenhouse gas emission coefficients were assigned using the Our World in Data dataset based on Poore and Nemecek. OWID reports exact values for several key categories, including beef from beef herds at 99.48 kg CO_2-eq/kg, lamb and mutton at 39.72, poultry meat at 9.87, eggs at 4.67, milk at 3.15, other pulses at 1.79, and wheat and rye at about 1.6 kg CO_2-eq/kg in the derivative visual materials built from the same database. Since the Turkish national diet aggregates foods into broad groups rather than product-level detail, the present study uses conservative category proxies rather than pretending to estimate item-level precision (Poore & Nemecek, 2018; Ritchie & Roser, n.d.). Accordingly, the following modelling coefficients are used:

Table 2. Assigned Greenhouse Gas Coefficients for the Simplified Model

Food group	**Assigned coefficient (kg CO_2-eq/kg)**	**Proxy logic**
Bread	1.60	wheat/rye proxy
Other cereals	1.60	cereal average conservative proxy

Vegetables	0.50	low-impact vegetable proxy
Fruits	0.65	mid-range fruit proxy
Milk and dairy products	3.15	milk proxy
Red meat	39.72	lamb/mutton proxy
Poultry	9.87	OWID poultry value
Eggs	4.67	OWID egg value
Legumes	1.79	OWID pulses value

Source: Prepared by the author.

Two modelling decisions should be noted. First, red meat is proxied by the lamb and mutton value rather than the beef-herd maximum because Turkish red-meat consumption is not exclusively beef and because this avoids overinflating the baseline estimate. Second, fruits and vegetables are assigned moderate proxy values because the observed survey categories pool heterogeneous foods with widely varying footprints. These are therefore stated explicitly as study-specific modelling assumptions, not as direct TNHS coefficients.

6.4. Theoretical Baseline Carbon-Footprint Calculation

The theoretical diet-related carbon footprint is calculated as:

$$\mathrm{CFT} = \sum \mathrm{j} = 1\mathrm{nQj} \times \mathrm{EFj}$$

where Qj is the daily quantity of food group j in kilograms and EFj is the greenhouse gas coefficient for that food group. Following this formula, the baseline Turkish basket produces the food-group contributions shown in Table 3.

Table 3. Theoretical Carbon Contributions Of The Observed Turkish Baseline Basket

Food group	Quantity (kg/day)	Emission factor	Carbon contribution (kg CO_2-eq/day)
Bread	0.1798	1.60	0.288
Other cereals	0.0736	1.60	0.118
Vegetables	0.2519	0.50	0.126
Fruits	0.1589	0.65	0.103
Milk and dairy products	0.1880	3.15	0.592
Red meat	0.0433	39.72	1.720
Poultry	0.0252	9.87	0.249
Eggs	0.0141	4.67	0.066

Source: Prepared by the author.

$$\mathrm{CFbaselineT} = 3.261\ \mathrm{kg\ CO_2} - \mathrm{eq/person/day}$$

This simplified baseline estimate is strikingly close to the 3.21 ± 2.07 kg CO_2-eq/person/day reported for the Turkish national diet by İlhan et al. (2023). The closeness of the two values suggests that the simplified basket-and-proxy method used here is sufficiently robust for scenario modelling in a conference-paper context. In other words, the model is not a decorative skeleton; it already walks on its own legs.

6.5. Mediterranean-Oriented Improvement Scenarios

Two modelled Mediterranean-improvement baskets were designed to operationalise dietary transition. These are not purporting to represent observed diets. They are scenario baskets that test how modest and stronger moves toward eating more Mediterranean-style might alter the theoretical carbon footprint. The scenario logic aligns with the Mediterranean-diet literature:

- lower red-meat quantity,
- small decrease in poultry and eggs,
- greater fruit and vegetable intake,

- coverage of legumes as a more potent plant-protein source.
- slight moderation of dairy and refined cereal dependence (Bôto et al., 2022; Lorca-Camara et al., 2024).

Scenario M1: Moderate Mediterranean improvement

- Bread: 170 g/day
- Other cereals: 70 g/day
- Vegetables: 280 g/day
- Fruits: 180 g/day
- Milk and dairy: 180 g/day
- Red meat: 30 g/day
- Poultry: 22 g/day
- Eggs: 12 g/day
- Legumes: 30 g/day

Scenario M2: Strong Mediterranean improvement

- Bread: 160 g/day
- Other cereals: 65 g/day
- Vegetables: 320 g/day
- Fruits: 200 g/day
- Milk and dairy: 170 g/day
- Red meat: 20 g/day
- Poultry: 18 g/day
- Eggs: 10 g/day
- Legumes: 50 g/day

Using the same coefficient structure, the theoretical carbon values of these baskets are:

$$\mathrm{CFM1T} = 2.726\ \mathrm{kg\ CO_2 - eq/person/day}$$

$$\mathrm{CFM2T} = 2.294\ \mathrm{kg\ CO_2 - eq/person/day}$$

Relative to the observed Turkish baseline value (3.261 kg CO_2-eq/day), the moderate Mediterranean scenario suggests decrease of nearly 16.4%, while strong Mediterranean scenario suggests a decrease of close to 29.7% (Table 7). The main contributor to this decrease is the reduction of red meat with still low mass share but higher carbon pressure due to its larger coefficient.

6.6. Incorporating Food Waste

Now, the task is to transition from that theoretical “plate” to the kitchen. This includes an adjustment for household food waste of 631 million tonnes in households in the UNEP's communication (2024), which amounts to approximately 79 kg per capita, but this study uses scenario coefficients instead of asserting observed Turkish household-waste rates on a direct comparability basis for the same sample type. Three waste levels are used:

- Low waste: W=0.05

- Medium waste: W=0.10
- High waste: W=0.20

The waste-adjusted carbon footprint is:

$$\mathrm{CFW} = \mathrm{CFT} \times (1 + \mathrm{W})$$

Applying this to the three baskets gives the results below.

Table 4. Waste-Adjusted Theoretical Carbon Footprints

Basket	Theoretical CF	Low waste (5%)	Medium waste (10%)	High waste (20%)
Baseline Turkish basket	3.261	3.424	3.587	3.913
M1 Moderate Mediterranean	2.726	2.863	2.999	3.272
M2 Strong Mediterranean	2.294	2.409	2.523	2.753

Source: Prepared by the author.

This table already reveals the central logic of the study. Mediterranean-oriented baskets remain lower-carbon in theory, but waste erodes part of the gain. Under high waste, the moderate Mediterranean basket rises from 2.726 to 3.272 kg CO_2-eq/day, nearly touching the observed Turkish baseline. The sustainability advantage does not disappear, but it becomes thinner and more fragile.

6.7. Mediterranean Efficiency Gap

The study's core analytical concept is now calculable:

$$\mathrm{MEGi} = \mathrm{CFiA} - \mathrm{CFiT}$$

where MEGi is Mediterranean Efficiency Gap. This is how much carbon is added back into a theoretically better diet through waste and behaviour. Zero means that household practice keeps the theoretical climate edge intact. A value above zero indicates that the kitchen has smoothed down the diet's green edge. This will be the link between the empirical calculations we do and how to interpret their behaviour in what follows.

7. Results and Discussion

7.1. Baseline Carbon Structure Of The Observed Turkish Basket

The first outcome of the modelling exercise is that the simplified observed Turkish basket produced a theoretical diet-induced carbon footprint of 3.261 kg CO_2-eq/person/day, which aligns closely with the value of 3.21 ± 2.07 kg CO_2-eq/person/day reported by İlhan et al. (2023) using TNHS 2017 data. The close approximation indicates that the simple basket-and-proxy method employed in this paper can be considered to provide a valid basis for scenario modelling rather than an entirely abstract construct. Methodologically speaking, the 'baseline estimate' works like a good compass: it doesn't pretend to millimetric precision but provides general direction.

A second key finding is about the internal make-up of the baseline footprint. Despite its numerical presence in the baseline basket contributing only 43.3 g/person/day of red meat, the associated emission coefficient assigned to red meat makes it by far the largest single calculated footprint contributor generating 1.720 kg CO_2-eq/day or more than half of total carbon burden modelled in this analysis. In contrast, although vegetables and fruits represent much larger volumes in physical terms compared to meat and dairy added together, their contribution to the total is far smaller due to the low coefficients assigned. This accords with a pattern widely evident in post-2015 literature: climate pressure in food systems is less driven by quantity than by carbon intensity of particular categories, most notably red meat.

Analytically, this finding is important for the discussion of the Mediterranean diet. It implies that even moderate departures from red meat can produce outsized carbon benefits, while significant changes in already low-carbon categories like vegetables have relatively smaller carbon impacts. In short, the carbon math of the kitchen is not equal; while some foods whisper, others come clomping in with leaden boots.

7.2. Carbon Effects Of Mediterranean-Oriented Dietary Improvement

The scenario analysis demonstrates that even a modest shift towards a Mediterranean-style basket yields a substantive reduction in hypothetical carbon intensity. M1 basket brings down this theoretical footprint to 2.726 kg CO_2-eq/person/day, a reduction of 16.4%. The M2 basket, which hypothesises a more pronounced decrease in red meat and broader increase in fruits, vegetables and legumes relative to the baseline, translates into an even lower footprint of 2.294 kg CO_2-eq/person/day, for a reduction of 29.7% against the mean Turkish baseline observed. These magnitudes are consistent with the literature suggesting that higher adherence to Mediterranean dietary pattern is associated with lower greenhouse gas emissions and other wider environmental benefits (Álvarez-Álvarez et al., 2024).

The form of these reductions is as important as their magnitude. It is not necessarily a blanket reduction of all food groups but rather a select rebalancing of the basket away from high-impact animal-source foods and toward lower-impact plant-based categories that accounts for the largest source of improvement. This adds to recent reviews finding that the sustainability benefit of the Mediterranean diet is tied to its food-group composition more than any abstract cultural designation imbued upon it. What this means in practice is that the model finds a Mediterranean-style diet to be climatically beneficial not because, for some symbolic reason, it should be Mediterranean, but rather because it has fewer carbon intensive foods structurally.

7.3. Food Waste As An Erosion Mechanism

Once we introduce food-waste scenarios, the climate edge of Mediterranean-oriented baskets holds, yet thins noticeably. When the (low, medium and high) waste coefficients based on UNEP's global evidence base are used, the baseline Turkish basket increases from 3.261 to 3.424, 3.587, and 3.913 kg CO_2-eq/day respectively. Using the same adjustment for the Mediterranean scenarios indicates that M1 increases from 2.726 to 2.863, 2.999, and 3.272 kg CO_2-eq/day in low-, mid-, and high-waste conditions; meanwhile, M2 rises from 2.294 to 2.409, 2.523 and 2.753 kg CO_2-eq/day across the same waste levels (Table 4). This pattern reflects one of the main messages in UNEP's 2024 report: that household food waste is not a secondary concern but rather an environmental multiplier, with households around the world wasting 631 million tonnes of food in 2022, or about 79 kg per person, and food waste more broadly being responsible for a significant portion of global environmental harm.

Under high waste, the M1 basket comes closest to the baseline, reaching 3.272 kg CO_2-eq/day against the observed baseline value of 3.261. The upshot is that a theoretically improved diet can lose most of its carbon edge if food is habitually wasted. The plate might get better, but the bin seeks a silent revenge. This result significantly reinforces the argument that dietary sustainability cannot be assessed based on composition alone. If a household gets better with dietary management but its kitchen writing is not yet efficient, it may seem to maintain higher quality in feeding against wrong, not benefiting in proportionate environmental improvements.

This finding is consistent with other behavioural food-waste studies. More recent studies over the years since 2015 highlight that household food waste is conditioned by planning, provisioning routines, storage practices, leftover use and everyday behavioural friction rather than by awareness alone. Thus, the previous waste-adjusted results of our current model are not merely mechanical figures derived from a theoretical footprint; they represent a wider conceptual shift in the literature from considering sustainability as a static dietary property to something lived and enacted by households.

7.4. Behavioural Profiles And Adjusted Carbon Outcomes

To move from the waste-adjusted kitchen to the behaviour-adjusted kitchen, the study applies the composite formulation introduced in Section 6:

$$\mathrm{CFiA} = \mathrm{CFiT} \times (1 + \mathrm{Wi} + \beta\mathrm{Bi} - \gamma\mathrm{Si})$$

For illustrative implementation, this paper uses β=0.20 and γ=0.15, with behaviour scores normalised between 0 and 1. Three stylised profiles are employed:

- Profile A: Environmentally conscious planner

  B=0.20, S=0.80, low waste W=0.05

- Profile B: Price-sensitive mixed consumer

  B=0.50, S=0.50, medium waste W=0.10

- Profile C: Convenience-oriented high-friction consumer

B=0.80, S=0.20, high waste W=0.20

Applying these profiles to the M2 strong Mediterranean basket produces the following adjusted outcomes:

- Profile A: CFA=2.225 kg CO_2-eq/day
- Profile B: CFA=2.581 kg CO_2-eq/day
- Profile C: CFA=3.051 kg CO_2-eq/day

The contrast is substantial. Transition from Profile A to Profile C, starting from the same theoretical Mediterranean-oriented basket, generates an additional adjusted footprint of 0.826 kg CO_2-eq/day. As compared to the theoretical M2 value of 2.294, Profile A's adjusted footprint of 2.225 marginally undercuts the theoretical estimate, while Profile C increases the footprint by approximately 33.0%. That implies that household behaviour is powerful enough to erode quite a lot of the low-carbon advantages of a healthier dietary pattern.

Applying the same medium-friction behavioural profile to both M1 and baseline baskets reveals an additional disaggregation. For Profile B, the baseline basket increases to 3.669 kg CO_2-eq/day and the M1 basket to 3.067 kg CO_2-eq/day. This still puts M1 under the baseline, but it narrows the gap significantly. When compared to the baseline unadjusted basket value of 3.261, this M1 mediated basket with medium behavioural friction only manages about 6.0% improvement. In short, dietary improvement still matters, but slovenly behaviour erodes its dividends.

7.5. The Mediterranean Efficiency Gap

The concept of the Mediterranean Efficiency Gap (MEG) provides a compact way to interpret the previous results:

$$\mathrm{MEGi} = \mathrm{CFiA} - \mathrm{CFiT}$$

For the M2 basket, the gap is:

- Profile A: MEG=−0.069MEG = -0.069MEG=−0.069
- Profile B: MEG=0.287MEG = 0.287MEG=0.287
- Profile C: MEG=0.757MEG = 0.757MEG=0.757

Behaviourally consistent individuals and households (MEG ≈ 0 or MEG < 0) behave in such a way that preserves, if not slightly increases, the theoretical sustainability potential of basket. In contrast, a large positive MEG means that the household does not translate its diet's theoretical climate benefit into an equally strong realised outcome. The high-friction scenario shows that while the Mediterranean basket still has a better profile than the initial baseline, much of its environmental potential is lost through waste and behaviour. The elegance of the dietary pattern is therefore not sufficient; execution is key.

The MEG concept also serves to unite two literatures that are frequently considered in isolation from each other: the dietary sustainability literature, which emphasises lower emissions from Mediterranean-style eating; and the household behaviour literature, which focuses on food waste and consumption routines. This study shows that both are right, but at different stages of the same chain. The Mediterranean diet may indeed be structurally lower-

carbon, yet whether that promise survives in the household depends on behavioural discipline, planning capacity, and waste intensity.

8. Conclusion

This study examined whether adherence to Mediterranean-style dietary patterns necessarily results in lower kitchen-related carbon footprints once household food waste and consumer behaviour are taken into account. The findings suggest that the answer is not always. In theoretical terms, Mediterranean-oriented baskets clearly perform better than the observed Turkish baseline basket, mainly because reducing red meat generates disproportionate carbon gains relative to its share in the daily basket. This is fully consistent with recent literature showing that the Mediterranean diet generally has a lower environmental burden than more animal-product-intensive dietary patterns (Bôto et al., 2022; Lorca-Camara et al., 2024).

However, once food waste is introduced, part of that environmental advantage begins to erode. The scenario analysis showed that waste can substantially narrow the carbon gap between the baseline basket and Mediterranean-improvement baskets. This aligns with the UNEP Food Waste Index Report 2024, which identifies households as a major source of food waste globally, and with household food-waste research emphasising that sustainability outcomes are strongly shaped by everyday planning, storage, and leftover-management practices (Boulet et al., 2021; UNEP, 2024; Vittuari et al., 2023).

The behavioural scenarios also showed that improving dietary quality by itself would not ensure environmental efficiency. Even a basket firmly aimed at the Mediterranean can lose a substantial amount of its climate advantage under conditions of convenience-based, poorly planned and high-waste in-household consumption. By contrast, a household profile defined by planning, seasonal and local purchasing, and more robust reusing of leftovers can maintain much more of the basket's theoretical potential for sustainable impact. This perspective is consistent with OECD evidence indicating that household food choices are influenced by affordability, taste, nutritional value, convenience and environmental concern instead of motivation on the environment alone (OECD, 2025).

Thus, the primary conceptual contribution of this paper is the Mediterranean Efficiency Gap, which captures how far reality in the kitchen has strayed from a diet's theoretical promise for climate mitigation. This idea serves as a bridge between two literatures that tend to be kept separate: the sustainable-diet literature, which considers diet composition, and the household food-waste literature, considering behavioural routines. The current study recommends that they need to be analysed together. A diet may appear sustainable at the point of selection, yet be less sustainable at the point of use.

From a policy point of view, the conclusion is obvious. Furthermore, promoting the Mediterranean diet through nutrition discourse alone is unlikely to achieve its full climate benefit. Public interventions should integrate healthy diet promotion with food-waste prevention, meal-planning support, storage literacy and portion management, along with behaviourally informed consumer guidance. In that light, we should not only think of sustainable diets in terms of what people choose to eat, but how people manage what they bring into the home.

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CURRENT APPROACHES AND METHODOLOGICAL DEVELOPMENTS IN SENTIMENT ANALYSIS: A LITERATURE REVIEW

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ABSTRACT

Sentiment analysis, as a rapidly evolving field within natural language processing, has undergone significant technological and methodological transformations over the past decade. This study systematically examines the methodological evolution, ranging from traditional rule-based and dictionary-based approaches, through machine learning methods and deep learning, to large language models. The research evaluates the fundamental techniques of sentiment analysis, their strengths, limitations, and effectiveness in real-world applications through a comprehensive literature review spanning from 2010 to 2025. Particular emphasis is placed on the improvements in sentiment classification achieved through transformer architectures and context-aware representations, as well as fine-grained methods such as aspect-based sentiment analysis and multilingual studies. Furthermore, practical challenges such as data quality, labelling reliability, imbalanced datasets and cultural context issues were discussed; studies conducted in Turkish and other low-resource languages were included.

Consequently, future research priorities such as explainable artificial intelligence, ethical issues and real-world applicability were identified.

Keywords: Sentiment Analysis, Deep Learning, Natural Language Processing.

DUYGU ANALİZİNDE GÜNCEL YAKLAŞIMLAR VE METODOLOJİK GELİŞMELER: BİR LİTERATÜR TARAMASI

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ÖZET

Duygu analizi, doğal dil işlemenin hızla gelişen bir alanı olarak, son on yılda teknolojik ve metodolojik açıdan önemli dönüşümler yaşamaktadır. İlgili çalışma, geleneksel kural tabanlı ve sözlük temelli yaklaşımlardan başlayarak, makine öğrenmesi yöntemlerinden derin öğrenmeye ve son olarak büyük dil modellerine uzanan metodolojik evrim sürecini sistematik olarak ele almaktadır. Araştırma, 2010'dan 2025'e kadar yapılmış kapsamlı literatür taraması ile duygu analizinin temel teknikleri, bunların güçlü yönleri, sınırlılıkları ve gerçek dünya uygulamalarındaki etkinliğini karşılaştırmalı biçimde değerlendirilmektedir. Özellikle dönüştürücü mimarisi ve bağlam duyarlı temsillerin duygu sınıflandırmasında sağladığı iyileştirmeler, özellik tabanlı duygu analizi gibi ince taneli yöntemler ve çok dilli çalışmalar vurgulanmaktadır. Ayrıca, veri kalitesi, etiketleme güvenilirliği, dengesiz veri setleri ve kültürel bağlam sorunları gibi pratik zorluklar tartışılmış; Türkçe ve diğer düşük kaynaklı dillerde yapılan çalışmalara yer verilmektedir. Sonuç olarak, açıklanabilir yapay zeka, etik sorunlar ve gerçek uygulanabilirlik gibi gelecekteki araştırma öncelikleri belirlenmektedir.

Anahtar kelimeler: Duygu Analizi, Derin Öğrenme, Doğal Dil İşleme.

1.Giriş

Dijital teknolojilerin yaygınlaşması, internet temelli iletişim kanallarının çeşitlenmesi ve sosyal medya platformlarının gündelik yaşamın merkezine yerleşmesi, son yıllarda çok büyük hacimli metinsel verinin üretilmesine yol açmaktadır. Kullanıcı yorumları, ürün ve hizmet değerlendirmeleri, çevrimiçi şikayetler, forum içerikleri, sosyal medya paylaşımları ve çeşitli dijital etkileşim biçimleri; bireylerin görüş, tutum ve duygularını doğrudan yansıtan zengin veri kaynakları olarak öne çıkmaktadır. Sözü edilen durum, metin verisinin yalnızca iletişimsel bir çıktı olarak değil, aynı zamanda sistematik olarak analiz edilebilecek önemli bir bilgi alanı olarak değerlendirilmesini mümkün kılmaktadır. Özellikle dijital ortamlarda üretilen verinin hız, hacim ve çeşitlilik bakımından sürekli artış göstermesi, sözü edilen verilerin otomatik olarak işlenmesine yönelik yöntemlere olan ilgiyi de artırmaktadır.

İlgili çerçevede duygu analizi, doğal dil işleme alanının en görünür, en dinamik ve en yaygın uygulama alanlarından biri haline gelmektedir. Duygu analizi genel olarak, metinsel ifadelerde yer alan öznel yargıların, görüşlerin, değerlendirmelerin ve duygusal yönelimlerin otomatik biçimde tanımlanmasını amaçlamaktadır. En temel düzeyde bir metnin olumlu, olumsuz ya da nötr yönelim taşıyıp taşımadığını belirlemeye odaklanan söz konusu alan, zaman içerisinde daha karmaşık ve daha ayrıntılı görevleri de kapsayacak biçimde gelişmektedir. Günümüzde duygu analizi yalnızca genel kutupsallığın belirlenmesiyle sınırlı kalmamakta; aynı zamanda özellik temelli değerlendirme, bağlama duyarlı yorumlama, duygu türlerinin ayrıştırılması, çok dilli işleme ve çok modlu çözümleme gibi daha ileri düzey görevleri de içermektedir. İlgili yönüyle duygu analizi, hem teknik hem de uygulamalı açıdan giderek genişleyen bir araştırma alanı niteliği taşımaktadır.

Duygu analizinin gelişim süreci, aynı zamanda doğal dil işleme literatüründeki daha geniş metodolojik dönüşümün de önemli bir yansıması olarak değerlendirilmektedir. Alanın ilk dönemlerinde daha çok kural tabanlı ve sözlük temelli yaklaşımlar öne çıkmaktadır. Sözü edilen yaklaşımlar, belirli sözcük listeleri, önceden tanımlanmış duygu sözlükleri ve dilbilimsel kurallar aracılığıyla metinlerdeki duygusal yönelimi belirlemeye çalışmaktadır. Söz konusu yöntemler, yorumlanabilirliklerinin yüksek olması, daha düşük hesaplama maliyeti gerektirmesi ve sınırlı veri koşullarında dahi uygulanabilir görünmesi bakımından önemli avantajlar sunmaktadır. Bununla birlikte, bağlamsal anlamı yeterince yansıtamama, ironi ve kinaye gibi karmaşık dilsel yapılarda yetersiz kalma ve kelimelerin metin içindeki ilişkilerini sınırlı biçimde değerlendirme gibi nedenlerle söz konusu yaklaşımlar belirli sınırlar taşımaktadır.

Daha sonraki dönemde geleneksel makine öğrenmesi yöntemleri duygu analizine yeni bir yön kazandırmaktadır. Naive Bayes, Destek Vektör Makineleri, Lojistik Regresyon ve Rastgele Ormanlar gibi yöntemler; metni sayısal olarak temsil eden tekniklerle bir araya gelerek duygu sınıflandırmasında yaygın biçimde kullanılmaktadır. Özellikle Bag-of-Words, N-gram ve TF-IDF gibi temsil biçimleri, metinsel verinin analiz edilebilir hale gelmesinde önemli rol oynamaktadır. Ancak söz konusu aşamada da öznitelik mühendisliğine duyulan ihtiyaç, kelime sırasının yeterince temsil edilememesi ve daha uzun bağlamsal ilişkilerin yakalanmasındaki güçlükler belirgin sınırlılıklar olarak ortaya çıkmaktadır. Sözü edilen nedenle alan, daha güçlü temsil kapasitesine sahip yöntemlere doğru evrilmektedir.

Derin öğrenme yaklaşımlarının duygu analizine uygulanması, sözü edilen dönüşümde önemli bir aşamaya işaret etmektedir. Özellikle yinelemeli sinir ağları, LSTM, GRU ve evrişimsel sinir ağları gibi mimariler, metin içindeki daha karmaşık örüntülerin ve sıralı ilişkilerin modellenmesine olanak tanımaktadır. Bunun ardından dönüştürücü mimarinin ve

önceden eğitilmiş dil modellerinin yaygınlaşması, duygu analizinde belirgin bir paradigma değişimi yaratmaktadır. BERT ve benzeri modeller sayesinde metin, yalnızca kelime düzeyinde değil, bağlam düzeyinde de daha güçlü biçimde temsil edilebilmektedir. Böylece duygu analizinde doğruluk, esneklik ve genellenebilirlik açısından daha gelişmiş sonuçlar elde edilebilmektedir. Bununla birlikte yöntemsel ilerleme yalnızca daha güçlü modellerin ortaya çıkması anlamına gelmemektedir. Aynı zamanda veri kalitesi, etiketleme güvenilirliği, sınıf dengesizliği, düşük kaynaklı dillerde performans, hesaplama maliyeti, açıklanabilirlik ve etik sorumluluklar gibi konular da araştırmaların merkezinde yer almaya devam etmektedir.

Özellikle İngilizce dışındaki dillerde duygu analizi çalışmaları, alanın metodolojik sınırlarını daha görünür hale getirmektedir. Türkçe gibi morfolojik açıdan zengin dillerde sözcük yapısının karmaşıklığı, esnek cümle düzeni, sosyal medya dilindeki kısaltmalar ve gündelik kullanım çeşitliliği, standart yöntemlerin doğrudan uygulanmasını güçleştirmektedir. Benzer biçimde düşük kaynaklı dillerde etiketli veri eksikliği, alan uyarlaması sorunları ve çapraz dilli öğrenmenin sınırlılıkları da önem taşımaktadır. Söz konusu nedenle duygu analizinde yöntem başarısı yalnızca model mimarisine değil, aynı zamanda kullanılan veri setinin niteliğine, dilin yapısal özelliklerine ve değerlendirme çerçevesine de bağlı görünmektedir.

Gerçekleştirilen çalışma, duygu analizinin tarihsel ve metodolojik gelişimini literatür temelli bir yaklaşımla incelemeyi amaçlamaktadır. Çalışmada, kural tabanlı ve sözlük temelli yöntemlerden başlayarak geleneksel makine öğrenmesi, derin öğrenme, dönüştürücü mimari ve büyük dil modellerine uzanan metodolojik dönüşüm sistematik biçimde ele alınmaktadır. Ek olarak, özellik temelli duygu analizi, çok modlu analiz, çok dilli ve düşük kaynaklı diller bağlamındaki uygulamalar, veri kalitesi ve etiketleme sorunları ile açıklanabilirlik, maliyet ve etik boyutlar da tartışılmaktadır. Böylece çalışma, duygu analizi literatüründe öne çıkan güncel yaklaşım ve metodolojik gelişmeleri yalnızca teknik performans bakımından değil, aynı zamanda uygulama olanakları ve sınırlılıkları bakımından da bütüncül bir çerçevede değerlendirmeyi hedeflemektedir. İlgili yönüyle çalışmanın, alandaki yöntemsel dönüşümü anlamaya ve gelecekteki araştırma yönelimlerini daha sağlıklı biçimde tartışmaya katkı sunacağı düşünülmektedir.

2. Literatür Taraması

2.1. Duygu Analizi: Kavramsal Temel ve Doğal Dil İşleme İçindeki Konumu

Duygu analizi, görüş analizi (opinion mining) olarak da bilinmektedir ve genel olarak metinsel veri içindeki öznel bilgileri çıkarıp yorumlamayı amaçlayan bir doğal dil işleme (Natural Language Processing, NLP) görevidir (Chitra vd., 2021). En temel biçimiyle duygu analizi, bir metnin pozitif, negatif ya da nötr bir duygusal yönelim taşıyıp taşımadığını belirlemeyi amaçlar. Bununla birlikte, alan son yıllarda önemli bir gelişim göstermiş; yalnızca duygu kutbunun tespitine odaklanmak yerine sevinç, üzüntü ve öfke gibi duygu türlerinin belirlenmesi, tutum analizi ve özellik-temelli duygu analizi gibi daha ayrıntılı yöntemleri de içerecek biçimde genişlemiştir (Nadeem vd., 2025).

Doğal dil işleme içindeki konumunu düşündüğümüzde, duygu analizi; metin madenciliği (text mining), sınıflandırma (classification), bilgi çıkarma (information extraction) ve anlamsal analiz gibi pek çok teknikten faydalanmaktadır. Özellikle son on beş yılda duygu analizi, NLP araştırmasının en yoğun çalışılan konusu haline gelmiş (Gunasekaran, 2023) ve e-ticaret, finans, sağlık ve pazarlama gibi alanlarda geniş uygulamalar bulmaktadır.

2.2. Geleneksel Yaklaşımlar: Kural Tabanlı ve Sözlük Temelli Yöntemler

Duygu analizinin tarihsel gelişiminde ilk aşama, kural tabanlı (rule-based) ve sözlük temelli (lexicon-based) yöntemlerle başlamaktadır. Söz konusu yaklaşımlar, önceden tanımlanmış duygu sözcükleri listeleri ve dilbilimsel kurallar kullanarak metinleri analiz etmektedir (Naithani & Raiwani, 2022). Örneğin, "harika", "mükemmel" gibi kelimeler pozitif, "kötü", "berbat" gibi sözcükler negatif olarak etiketlenmektedir.

Sözlük tabanlı yöntemler, düşük hesaplama kaynağı gerektirmeleri, kolay yorumlanabilmeleri ve küçük veri setlerinde de uygulanabilmeleri bakımından önemli avantajlar sunmaktadır. Bununla birlikte, söz konusu yaklaşımlar bağlamsal anlama, ironi ve kinayeli ifadeleri kavramakta ciddi sınırlılıklar göstermekte (Albladi vd., 2025), kelime sıralamasını ihmal etmektedir.

Geleneksel makine öğrenmesi yöntemleri (Naive Bayes, Support Vector Machine (SVM), Logistic Regression, Random Forest vb.) sözlük yaklaşımlarına paralel ve onlardan bağımsız olarak geliştirilmiştir (Gunasekaran, 2023). Sözü edilen yöntemler, öznitelik mühendisliği (feature engineering) ile N-gram, Bag-of-Words veya TF-IDF gibi temsil tekniklerinden yararlanmaktadır. Sözü edilen yöntemler, metin verisini analiz edilebilir hale getirmek için farklı temsil tekniklerinden yararlanmaktadır. N-gram yaklaşımı, metindeki ardışık kelime ya da kelime gruplarını dikkate alarak yerel bağlam örüntülerini ortaya çıkarmayı amaçlamaktadır. Bag-of-Words yöntemi, kelimelerin metin içindeki sıklığına odaklanırken sözcüklerin sırasını göz ardı etmektedir. TF-IDF ise bir kelimenin yalnızca metinde kaç kez geçtiğini değil, aynı zamanda tüm belge kümesi içindeki ayırt ediciliğini de dikkate alarak daha anlamlı bir ağırlıklandırma sunmaktadır. Literatürdeki bulgular, BERT tabanlı yöntemlerin geleneksel makine öğrenmesi yaklaşımlarına kıyasla daha yüksek performans sergilediğini göstermektedir (Diri vd., 2025). Bununla birlikte, söz konusu modellerin temel sınırlılığı, kelime sırasına duyarsız olmaları ve uzun bağlamsal ilişkileri etkili biçimde yansıtamamalarıdır.

2.3. Kelime Gömmelerinin Yükselişi: Word2Vec, GloVe ve FastText

2000'li yılların sonundan itibaren, statik kelime gömmelerinin ortaya çıkışı duygu analizi araştırmasında bir dönüm noktası oluşturmaktadır (Raditya vd., 2026). Word2Vec, GloVe ve FastText gibi teknikler, kelimelerin anlamsal ve sentaktik ilişkilerini yoğun vektörler olarak temsil etme kabiliyeti vermekte, böylece modellerin işlenmiş verinin niteliği önemli ölçüde artırılmaktadır. Word2Vec, GloVe ve FastText gibi teknikler, kelimelerin anlamsal ve sözdizimsel ilişkilerini yoğun vektörler aracılığıyla temsil etmeyi mümkün hale getirmektedir. Word2Vec, bağlam temelli öğrenme yaklaşımıyla benzer kullanıma sahip kelimeleri yakın vektör uzaylarında konumlandırmaktadır. GloVe, kelime eşdizimlilik istatistiklerinden hareketle daha geniş ölçekli anlamsal ilişkileri yakalamakta; FastText ise kelime içi alt birimleri dikkate alarak özellikle biçimbilimsel açıdan zengin dillerde daha etkili temsiller sağlamaktadır.

Word2Vec'in CBOW ve Skip-Gram varyantları, benzer bağlamlarda kullanılan kelimelerin vektörel olarak birbirine yakın olmasını sağlamaktadır (Ladayya vd., 2025). GloVe, küresel kelime-kelime birlikte ortaya çıkma matrisini kullanarak, Word2Vec'e kıyasla daha istikrarlı ve anlamsal ağırlıklandırmaya daha duyarlı temsiller üretmektedir. FastText ise, karakter n-gramlarını dikkate alarak, morfolojik açıdan zengin dillerde ve yazım hatalarına karşı daha dayanıklı gömmeler sağlamaktadır (Tbaikhi vd., 2024).

Araştırmalar, sözcük gömmelerinin çeşitli kombinasyonlarının duygu sınıflandırması üzerindeki etkileri karşılaştırmakta ve öznitelik seçimine ve model mimarisine bağlı olarak performans farkları gözlemlenmektedir (Liu, 2024). Özellikle alan uyarlamalı (domain-adapted) gömmeler, genel amaçlı gömmelerden daha iyi sonuç vermektedir (Deniz vd., 2021).

2.4. Derin Öğrenme Dönüşümü: RNN, LSTM ve GRU Mimarilerinin Etkinliği

Derin öğrenmenin duygu analizine uygulanması, 2010'lar ortalarından itibaren hızla artmış (Kumar vd., 2025), temel olarak Yinelemeli Sinir Ağları (Recurrent Neural Networks, RNN), Uzun Kısa Süreli Bellek (Long Short-Term Memory, LSTM) ve Kapılı Yinelemeli Birim (Gated Recurrent Unit, GRU) mimarilerine dayanmaktadır. Söz konusu modellerin temel avantajı, sıralı veriyi işleyerek uzun süreli bağımlılık ilişkilerini öğrenebilmeleridir. Sözü edilen özellik, statik kelime gömmeleriyle elde edilmesi güç olan bir kapasite sunmaktadır.

LSTM (Trimukhe vd., 2024), gradyan kayboluşu (vanishing gradient) sorununu hallederek, çok katmanlı ağlarda eğitimi olanaklı kılmaktadır. İki yönlü LSTM (Bidirectional LSTM, BiLSTM), metni hem ileri hem geri yönde işleyerek, her kelimenin hem önceki hem sonraki bağlamını kavrayabilmektedir. GRU, LSTM'ye kıyasla daha az parametre gerektirerek, benzer performans sağlarken eğitimi daha hızlı yapabilmektedir (Elverişli & Taskiran, 2024).

Evrişimsel Sinir Ağları (Convolutional Neural Networks, CNN), duygu sınıflandırmasında yerel n-gram örüntülerini çıkarmada etkili olmaktadır (Ogundoyin vd., 2025). CNN'lerin paralel işleme kapasitesi ile LSTM'lerin sıralı bağlamı dikkate alabilme yeteneği, hibrit CNN-LSTM mimarilerinin geliştirilmesine zemin hazırlamaktadır (Rishu vd., 2024). Araştırmalar, söz konusu hibrit yapıların birçok veri kümesinde ve farklı duygu analizi görevlerinde, tek başına kullanılan CNN veya LSTM tabanlı modellere kıyasla daha yüksek sınıflandırma performansı sunabildiğini göstermektedir (Dang vd., 2021; Sorour vd., 2024).

Ek olarak, derin öğrenme modelleri yüksek hesaplama maliyeti gerektirmekte ve çok miktarda etiketli veriye ihtiyaç duymakta ve kara kutu sorunuyla karşı karşıya kalmaktadır (Islam vd., 2024). Ayrıca, ironi ve kinayeli ifadeleri anlamakta dahi çok katmanlı LSTM'ler sınırlı başarı göstermektedir.

2.5. Dönüştürücü Mimarisi ve Bağlam Duyarlı Temsiller: Paradigma Değişimi

Dönüştürücü mimarisi (2017 yılındaki " İhtiyacınız Olan Tek Şey Dikkat (Attention is All You Need)" çalışması ile tanıtıldıktan sonra), duygu analizi dahil olmak üzere NLP görevlerinde devrim yaratmaktadır. Dönüştürücü, dikkat mekanizması (attention mechanism) vasıtasıyla metnin tamamını paralel işleyerek, her kelime için tüm diğer kelimelerin etkisini hesaplayabilmektedir (Li, 2025). Söz konusu özellik, RNN'lerin ardışık doğası nedeniyle elde edilemeyen bir avantaj olarak öne çıkmaktadır.

BERT (Bidirectional Encoder Representations from Transformers) ve sonrasındaki çalışmalar (RoBERTa, DistilBERT, ALBERT vb.) (Kale & Mendhe, 2025), önceden eğitilmiş bağlam duyarlı temsillerin gücünü ortaya koymaktadır. BERT, geniş bir metin koleksiyonu üzerinde maskeli dil modeli olarak ön eğitim aldıktan sonra, ince ayar süreciyle duygu sınıflandırması gibi belirli doğal dil işleme görevlerine uyarlanabilmektedir. Araştırma bulguları, BERT tabanlı yöntemlerin geleneksel makine öğrenmesi yaklaşımları ile statik gömme temelli yöntemlere kıyasla daha yüksek performans sergilediğini ortaya koymaktadır (Diri vd., 2025). Birçok karşılaştırmalı değerlendirmede, söz konusu modellerin çeşitli standart veri kümelerinde %90'ın üzerinde doğruluk düzeyine ulaştığı görülmektedir.

RoBERTa, BERT'ü daha iyi eğitim stratejileri ile iyileştirerek (Kumar vd., 2025), DistilBERT ise öğrenci modelleme (knowledge distillation) kullanarak boyutu %40 azaltırken performansı korumayı başarmaktadır. Çok dilli BERT (mBERT), XLM-RoBERTa gibi modeller, çapraz dilli transfer öğrenmesine imkan tanıyarak, düşük kaynaklı diller için önemli bir çözüm olmaktadır.

2.6. Büyük Dil Modelleri ve Yeni Paradigma: Sıfır Örnekli Öğrenme ve Açıklama Üretimi

Yakın dönemdeki GPT serisi, PaLM, Claude ve benzeri büyük dil modelleri (Large Language Models, LLM) (Ren, 2024), duygu analizini yeniden şekillendirmektedir. Söz konusu büyük dil modellerinin temel farklılığı, denetimli ince ayarlamaya ihtiyaç duymaksızın, doğal dil talimatları (prompts) vasıtasıyla pek çok görevi gerçekleştirebilmeleridir. Sıfır örnekli (zero-shot) ve az örnekli (few-shot) sınıflandırma yaklaşımlarının, kinayeli ifadelerin çözümlenmesinde ve çok dilli senaryolarda etkili sonuçlar verdiği bildirilmektedir (Alotaibi & Nadeem, 2024).

Ek olarak, büyük dil modelleri bazı önemli sınırlılıkları da beraberinde getirmektedir. Söz konusu sınırlılıklar arasında saydamlık eksikliği, yüksek hesaplama maliyeti, tekrar üretilebilirlik sorunları ile önyargı ve etik kaygılar öne çıkmaktadır (Ren, 2024). Ayrıca, FinBERT gibi belirli alanlara özgü olarak ince ayar yapılmış modellerin, bazı görevlerde genel amaçlı GPT tabanlı modellere kıyasla daha başarılı sonuçlar verdiği de görülmektedir (Almarzoog vd., 2025).

2.7. Güncel Metodolojik Gelişmeler: Özellik Temelli, Duygu ve Çok Modlu Analiz

Son yıllarda, basit pozitif/negatif polarite sınıflandırmasından öteye gidilerek, duygu analizinin kapsamı genişlemektedir. Özellik temelli duygu analizi (Aspect-based sentiment analysis, ABSA), bir ürün incelemesinden, "batarya ömrü" yönü için negatif, "ekran kalitesi" yönü için pozitif duygu çıkarabilmektedir (Hussain vd., 2025). Böylece, müşteri geri bildirilerinden daha işlem yapılabilir bilgiler çıkarılabilmektedir.

Emotion detection, sadece polariteden ziyade, sevinç, öfke, üzüntü, korku gibi belirli duygu kategorilerini tanımlamayı hedeflemektedir (Alqarni vd., 2025). İlgili doğrultuda, GoEmotions gibi veri kümeleri aracılığıyla daha ince ayrımlara dayalı duygu sınıflandırmaları gerçekleştirilmektedir.

Çok modlu duygu analizi, metin, görüntü ve ses gibi birden fazla veri kaynağını bütünleştirerek (Yang vd., 2024), sosyal medyada emojiler ve görsellerin duygusal bileşkesini yakalayabilmektedir. CNN'ler görsel özellikleri, BERT metin özelliklerini çıkarırken, dikkat mekanizmaları farklı veri kaynaklarını birleştirmektedir.

Diyalog temelli duygu analizi (Conversational sentiment analysis, CSA) birden fazla konuşmacı ve çok dönüşlü diyaloglar içindeki duygu değişmelerini takip etmeye çalışmaktadır. Alan uyarlaması, bir alanda eğitilmiş model ile başka alana uyarlanması gerektiğinde (Bao vd., 2025), kaynak ve hedef alan arasındaki farkı minimize edecek şekilde yapılandırılmaktadır

2.8. Çok Dilli ve Düşük Kaynaklı Diller: Sorunlar ve Çözümler

Duygu analizinin uluslararası boyutu, özellikle düşük kaynaklı dillerde ciddi zorluklar sunmaktadır. Türkçe gibi morfolojik açıdan zengin bir dil, N-gram temelli yaklaşımları ve basit sözcük birimlerine ayırmayı (tokenizasyon) yetersiz bırakmaktadır (Kiziltepe vd., 2025). Arap

dili, Hindi, Bangla ve Afrika dilleri üzerine çalışmalar (Aliyu vd., 2024), dönüştürücü modellerin çapraz dilli transfer potansiyelini gösterse de, çoğu durumda hala İngilizce kadar yüksek performans elde edilememektedir.

Çok dilli BERT (mBERT) ve XLM-RoBERTa gibi modeller, yüzden fazla dilden metin ile ön eğitilse de, az temsil edilen diller için optimal olmayabilmektedir (Hamim vd., 2025). Literatürde, ilgili güçlüğün giderilmesine yönelik olarak alan uyarlamalı ince ayar, çekişmeli eğitim ve denetimsiz alan uyarlaması gibi çeşitli teknikler önerilmektedir (Darak vd., 2025). Ayrıca, etiketli verinin sınırlı olduğu durumlarda az örnekli öğrenme ve meta-öğrenme yaklaşımları da önemli çözüm yolları arasında gösterilmektedir (Hu vd., 2023).

Türkçe özelinde, kaynak yetersizliğinin yanı sıra, dilsel özellikler de duygu analizi açısından önemli metodolojik güçlükler doğurmaktadır. Morfolojik yapı, çokça sıfat türetme, cümle yapısının esnekliği, sosyal medyada kısaltma ve argo yoğunluğu standart NLP süreçlerini karmaşıklaştırmaktadır. Söz konusu zorluğa rağmen, son dönem Türkçe-BERT modelleri (BERTurk, dbmdz BERT) Türkçe duygu analizinde umut verici sonuçlar sunmaktadır (Hadiwijaya vd., 2023).

2.9. Veri Kalitesi, Etiketleme ve Değerlendirme Zorlukları

Duygu analizinin başarısı veri setinin kalitesi ile yoğun olarak ilişkilidir. İnsan kodlayıcılar arası uyum (inter-annotator agreement), Cohen's Kappa veya Fleiss' Kappa gibi ölçütlerle hesaplanmaktadır. Birçok veri seti, söz konusu uyum oranında %70-80 civarında kalmaktadır; %90'ın üzerinde uyum yüksek seviyelendirilmektedir.

Sosyal medya verisi, doğası gereği gürültülü, yazım hatası ve argo içermektedir. Sınıf dengesizliği sorunu (örneğin pozitif incelemelerin %80, negatif incelemelerin %20 olması) sınıflandırıcının çoğunluk sınıfına yönelik önyargılı olmasına sebep olmaktadır (Rathje vd., 2024). SMOTE (Synthetic Minority Over-sampling Technique) gibi teknikler veya ağırlıklı kayıp fonksiyonları (weighted loss functions) söz konusu sorunla başa çıkmaya çalışmaktadır.

Ironik ve kinayeli ifadelerin tespiti, en zor görevlerden biridir. Duygusal polarite tam tersine döndüğünde, hatta model tarafından algılanamamaktadır. Emojiler, kültürel bağlam ve sosyal dinamikler, eğer model sözü edilen faktörleri görmezse yüksek hata oranlarına yol açmaktadır (Dubey vd., 2025).

Duygu analizi çalışmalarında kullanılacak değerlendirme ölçütlerinin seçimi büyük önem taşımaktadır. Doğruluk, kesinlik, duyarlılık ve F1 skoru gibi ölçütler, model performansının farklı yönlerden değerlendirilmesine imkan tanımaktadır. Ancak dengesiz veri setlerinde doğruluk ölçütü tek başına yanıltıcı sonuçlar verebilmektedir. Söz konusu nedenle makro F1 skoru, tüm sınıfları eşit biçimde dikkate alan bir ölçüt olarak öne çıkarken; mikro F1 skoru, sınıf frekanslarını esas alan ağırlıklı bir değerlendirme sunmaktadır (Rathje vd., 2024). Bunun yanı sıra hata matrisi, modelin hangi sınıfları birbiriyle karıştırdığını göstermesi bakımından önemli bir analiz aracı olarak değerlendirilmektedir.

2.10. Eleştirel Değerlendirme: Performans, Açıklanabilirlik ve Maliyet Boyutları

Akademik çalışmalar genellikle standart karşılaştırmalı veri setlerinde yüksek doğruluk elde etmeye odaklanmakta, ancak gerçek dünya uygulamalarının farklı ihtiyaçlarını görmezden gelmektedir. Bir finansal kurum, %98 doğruluk elde etmekten ziyade, nadir ancak kritik

senaryoları (örneğin fırıncı düzeyinde olumsuz geri dönüş) yakalayan bir model isteyebilmektedir.

Dönüştürücü modeller, birçok görevde üstün performans gösterse de, hesaplama maliyetleri modellerin önemli bir dezavantajıdır. DistilBERT gibi sıkıştırılmış modeller, performansta küçük düşüş ile birlikte çalışma hızını %40 artırabilmektedir (Ali vd., 2024). Sınırlı kaynaklar olan kuruluşlar için, geleneksel SVM+TF-IDF kombinasyonu çoğu zaman yeterli ve uygulanabilir olmaya devam etmektedir.

Açıklanabilirlik (explainability) de önemli bir husus olarak konumlanmaktadır. LIME, SHAP gibi post-hoc açıklayıcılık yöntemleri (Chamekh vd., 2025), modelin neden belirli bir sonuca varmış olduğunu gösterebilmekte ancak, dönüştürücü modellerin binlerce parametresinin tamamını açıklamak hala zorlu bir görev olarak karşımıza çıkmaktadır. Düşük kaynaklı dillerde çalışan araştırmacılar, bazen daha basit, yorumlanabilir modeller tercih edebilmektedir.

3. Sonuç

Duygu analizi alanı, son yıllarda hem kuramsal kapsamı hem de teknik araçları bakımından dikkat çekici bir dönüşüm geçirmektedir. Kural tabanlı ve sözlük temelli ilk yaklaşımlardan başlayarak geleneksel makine öğrenmesi yöntemlerine, oradan derin öğrenme ve dönüştürücü tabanlı modellere uzanan gelişim çizgisi, alanın giderek daha karmaşık metinsel yapıları işleyebilen bir yapıya kavuştuğunu göstermektedir. Söz konusu dönüşüm, yalnızca sınıflandırma başarısındaki artışla sınırlı kalmamakta; aynı zamanda metin içindeki bağlamın, anlam katmanlarının ve ince duygu ayrımlarının daha etkili biçimde temsil edilebilmesine de olanak tanımaktadır. İlgili nedenle duygu analizinin gelişimi, doğal dil işleme alanındaki yöntemsel ilerlemenin somut ve güçlü örneklerinden biri olarak değerlendirilmektedir.

Literatür genel olarak incelendiğinde, hiçbir yöntemin tüm problem türleri, tüm veri yapıları ve tüm dilsel bağlamlar için tek başına ideal bir çözüm sunduğunu söylemek güç görünmektedir. Geleneksel yaklaşımlar; yorumlanabilirlik, düşük maliyet ve uygulama kolaylığı bakımından belirli bağlamlarda anlamlı bir seçenek sunmaktadır. Buna karşılık derin öğrenme ve dönüştürücü tabanlı modeller, bağlam duyarlılığı ve temsil gücü açısından daha ileri sonuçlar üretmektedir. Büyük dil modelleri ise sıfır örnekli ve az örnekli öğrenme gibi yeni imkanlar sağlayarak alanı daha esnek bir yapıya taşımaktadır. Ancak şeffaflık, tekrar üretilebilirlik, hesaplama maliyeti, önyargı riski ve etik sorumluluk gibi meseleler sözü edilen modellerin kullanımının dikkatle değerlendirilmesini gerektirmektedir. Söz konusu durum, duygu analizinde yöntem seçiminin yalnızca performans oranlarına göre değil; araştırma amacı, veri niteliği, uygulama bağlamı, dilsel yapı ve teknik imkanlar dikkate alınarak yapılmasının daha dengeli bir yaklaşım sunduğunu göstermektedir.

Çalışmada incelenen literatür, duygu analizinin yalnızca teknik bir sınıflandırma problemi olarak ele alınmasının yeterli olmadığını da ortaya koymaktadır. Model başarımı kadar, kullanılan veri setinin niteliği, etiketleme sürecinin güvenilirliği, değerlendirme ölçütlerinin uygunluğu ve uygulama koşullarının gerçekçiliği de sonuçların anlamlılığı üzerinde doğrudan etkili olmaktadır. Özellikle sosyal medya verilerinde görülen yazım düzensizlikleri, argo kullanımı, kültürel referanslar, ironi ve kinaye gibi dilsel özellikler, duygu analizinin doğruluğunu ve genellenebilirliğini zorlaştırmaktadır. Benzer biçimde sınıf dengesizliği, düşük kaynaklı dillerde veri eksikliği ve alanlar arası farklılıklar da mevcut modellerin performansını sınırlayan temel etkenler arasında yer almaktadır. Söz konusu nedenle literatürde bildirilen

yüksek başarı oranlarının, veri seti bağlamı ve yöntemsel koşullar dikkate alınarak yorumlanması önem taşımaktadır.

Çalışmanın ortaya koyduğu önemli bulgulardan biri de, duygu analizindeki yöntemsel ilerlemenin doğrusal bir üstünlük ilişkisi biçiminde değil, daha çok çeşitlenen ihtiyaçlara verilen farklı yanıtlar şeklinde okunmasının daha doğru olduğudur. Bir başka ifadeyle, yeni modellerin ortaya çıkması eski yöntemleri bütünüyle işlevsiz hale getirmemektedir. Aksine, düşük maliyetli ve açıklanabilir çözümlerin gerekli olduğu durumlarda daha basit yöntemler hala işlevsel olabilmektedir. Buna karşılık daha karmaşık bağlamsal yapıların çözümlenmesi gereken görevlerde derin öğrenme ve dönüştürücü tabanlı yaklaşımlar daha güçlü bir seçenek haline gelmektedir. Dolayısıyla alanda yöntemsel tercih, tek bir "en iyi model" arayışından çok, belirli bir araştırma sorusu ve uygulama bağlamı için en uygun yöntemin belirlenmesi ekseninde şekillenmektedir.

Türkçe gibi morfolojik açıdan zengin ve görece düşük kaynaklı diller bağlamında ise literatür, hem umut verici gelişmelere hem de devam eden sınırlılıklara işaret etmektedir. Önceden eğitilmiş dil modelleri ve ince ayar teknikleri sayesinde sözü edilen dillerdeki duygu analizi performansı giderek artmaktadır. Ancak veri seti çeşitliliğinin sınırlı olması, farklı alanlar için yeterli etiketli kaynak bulunmaması ve dilin yapısal özelliklerinin modellemeyi zorlaştırması gibi nedenlerle araştırma ihtiyacı sürmektedir. Sözü edilen nedenle Türkçe ve benzeri dillerde yapılacak çalışmaların, yalnızca model denemelerine değil; aynı zamanda nitelikli veri seti üretimine, alan uyarlamasına ve kültürel bağlamı dikkate alan değerlendirme çerçevelerine de yönelmesi yararlı görünmektedir.

Söz konusu genel değerlendirmeler ışığında, çalışmadan çıkarılabilecek bazı temel noktalar öne çıkmaktadır. Kural tabanlı ve sözlük temelli yöntemler, özellikle küçük veri kümeleriyle çalışılan ve yüksek yorumlanabilirlik düzeyinin önem taşıdığı araştırmalarda işlevsel bir başlangıç noktası sunmaktadır. Buna karşılık geleneksel makine öğrenmesi yöntemleri, uygun öznitelik çıkarımı ve metin temsili teknikleriyle bir araya getirildiğinde, hala dengeli ve uygulanabilir sonuçlar verebilmektedir. Derin öğrenme tabanlı yaklaşımlar ise sıralı yapıların ve daha karmaşık örüntülerin öğrenilmesi bakımından duygu analizini daha ileri bir aşamaya taşımaktadır. Benzer biçimde dönüştürücü tabanlı modeller ve önceden eğitilmiş dil modelleri, bağlama duyarlı temsiller sayesinde alanda güçlü bir paradigma değişimi yaratmaktadır. Bunun yanında büyük dil modelleri, çok dilli ve esnek görev kurgularında dikkat çekici olanaklar sunmakta; ancak şeffaflık ve etik sorumluluk bakımından daha dikkatli değerlendirilmesi gereken bir çerçeve ortaya koymaktadır. Öte yandan veri kalitesi, etiketleme güvenilirliği ve değerlendirme ölçütleri de en az model performansı kadar belirleyici unsurlar arasında yer almaktadır. Son olarak Türkçe ve diğer düşük kaynaklı diller açısından bakıldığında, veri seti geliştirme, alan uyarlaması ve dilsel özellikleri dikkate alan modelleme ihtiyacı önemini sürdürmektedir.

Gelecekteki çalışmalar açısından bazı yönelimlerin daha fazla öne çıkması beklenmektedir. Öncelikle düşük kaynaklı diller için daha dengeli, kapsamlı ve güncel veri kümelerinin geliştirilmesi, alandaki karşılaştırmalı çalışmaların niteliğini artırabilir. Ek olarak, kültürel bağlama duyarlı ve alan özelinde uyarlanmış modellerin yaygınlaştırılması, yalnızca genel performans artışı değil, aynı zamanda daha güvenilir ve daha anlamlı sonuçlar elde edilmesine de katkı sunabilir. Açıklanabilir yapay zeka yaklaşımlarının duygu analizi ile birlikte ele alınması, özellikle karar destek sistemlerinde güven ve şeffaflık bakımından daha güçlü bir çerçeve oluşturabilir. Ayrıca performans ölçütlerinin yanında etik, adalet, güvenilirlik ve tekrar üretilebilirlik boyutlarının da değerlendirmelere dahil edilmesi, alanın yalnızca teknik değil, metodolojik ve toplumsal açıdan da olgunlaşmasına katkı sağlayabilir. Büyük dil modellerinin

sunduğu esneklik ile daha denetlenebilir ve daha açıklanabilir yöntemlerin birlikte düşünülmesi de önümüzdeki dönemde önemli bir tartışma alanı oluşturmaktadır.

Sonuç olarak duygu analizi, yalnızca teknik başarı oranlarıyla açıklanabilecek dar bir sınıflandırma problemi değildir. Alan; dilsel yapı, bağlam, veri niteliği, hesaplama maliyeti, açıklanabilirlik, etik sorumluluk ve uygulama amacı gibi çok sayıda boyutu birlikte içeren çok katmanlı bir araştırma ve uygulama alanı olarak şekillenmektedir. Sözü edilen nedenle gelecekteki ilerlemenin yalnızca daha yüksek doğruluk sağlayan modeller geliştirilmesine değil, aynı zamanda daha şeffaf, daha dengeli, daha açıklanabilir, daha etik ve farklı dilsel bağlamlara daha uyumlu yaklaşımların geliştirilmesine bağlı olduğu anlaşılmaktadır. İlgili yönüyle duygu analizi, hem metodolojik yeniliklerin hem de eleştirel değerlendirme ihtiyacının birlikte sürdüğü dinamik bir araştırma alanı olmaya devam etmektedir.

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EDUCATIONAL ECOSYSTEMS IN HIGHER EDUCATION: A STRATEGIC ORIENTATION FOR VIETNAMESE UNIVERSITIES IN THE DIGITAL ERA

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ABSTRACT

This paper develops a comprehensive analytical framework for university governance within a digital educational ecosystem in the context of globalization and Vietnam's ongoing national digital transformation. Grounded in international theoretical perspectives—particularly ecosystem theory, digital governance, and knowledge ecosystem approaches—the study conceptualizes higher education institutions as dynamic, multi-layered systems characterized by continuous interactions among human, technological, institutional, and socio-cultural dimensions.

The analysis integrates global frameworks, especially those advanced by OECD and UNESCO, with a contextual examination of Vietnam's higher education landscape. It identifies critical structural gaps in governance models, digital capacity, and ecosystem connectivity that constrain institutional adaptability and innovation. A central contribution of this study is its emphasis on personalization, positioning both learners and educators as active agents in the co-construction of knowledge ecosystems rather than passive participants.

Building on theoretical synthesis and extensive academic and practical experience, the paper proposes five strategic directions to foster more adaptive, data-driven, and human-centered university ecosystems. These include transforming digital governance structures, strengthening stakeholder competencies, enhancing ecosystem linkages, aligning policy frameworks, and cultivating a culture of innovation.

Keywords: educational ecosystem; digital governance; higher education; digital transformation; knowledge ecosystem; personalization

1. Introduction

Higher education worldwide is undergoing a profound paradigm shift, moving from institution-centered models toward ecosystem-based approaches in which universities operate as interconnected nodes within broader socio-technical systems (Barnett, 2018; Williamson, 2019). This transition is driven by rapid advances in digital technologies, the growing prominence of knowledge economies, and increasing demands for flexible and personalized learning experiences (OECD, 2021).

From this perspective, digital education ecosystems extend beyond technological infrastructure to encompass governance structures, policy frameworks, and patterns of stakeholder interaction that collectively shape educational processes and outcomes (OECD, 2023; UNESCO, 2023). Consequently, digital transformation should not be understood merely as the adoption of new technologies, but as a systemic reconfiguration of how education is organized, delivered, and continuously improved (Selwyn, 2016).

In Vietnam, digital transformation in education has gained significant policy attention, particularly within national strategies aimed at developing a digital economy (Prime Minister of Vietnam, 2020). Despite this momentum, implementation across higher education institutions remains uneven. In many cases, technological adoption has outpaced institutional integration, resulting in fragmented systems that limit the transformative potential of digitalization (Dang & Pham, 2022).

Drawing on extensive experience in educational research and teacher development, this study argues that the core challenge is not the availability of digital tools, but the absence of a coherent educational ecosystem capable of supporting continuous learning, innovation, and personalization. Without such a systemic foundation, digital initiatives risk remaining superficial and unsustainable (Bates & Sangrà, 2020).

Accordingly, this paper aims to develop a strategic framework to guide Vietnamese universities in building adaptive, sustainable, and human-centered educational ecosystems. The proposed framework emphasizes the integration of governance, technology, and human agency, with personalization positioned as a central organizing principle (Redecker, 2017).

2. Theoretical Background and Current Situation

2.1. Global Theoretical Foundations

The concept of an educational ecosystem is rooted in ecological systems theory, most notably articulated by Bronfenbrenner (1979), who conceptualized human development as occurring within nested systems of interaction between individuals and their environments. When applied to education, this perspective has evolved into a systemic understanding of learning as a dynamic, relational, and context-dependent process (Jackson, 2013).

In contemporary higher education discourse, this concept has been further extended into digital education ecosystems. These ecosystems integrate multiple interdependent dimensions, including human actors (students, educators, administrators), technological infrastructures (such as learning management systems, artificial intelligence, and data analytics), institutional governance mechanisms, and broader socio-cultural and policy environments (Williamson, 2019; OECD, 2021). Rather than functioning in isolation, these elements interact continuously, forming complex adaptive systems characterized by co-evolution and feedback loops (Holland, 2014).

International frameworks reinforce this systemic perspective. The OECD emphasizes that effective digital education ecosystems require holistic, multi-level governance approaches that connect micro-level learning processes, meso-level institutional management, and macro-level policy environments, while addressing key educational goals such as quality, equity, and efficiency (OECD, 2021; OECD, 2023). Similarly, UNESCO highlights the importance of open knowledge systems, collaboration, and shared learning cultures as foundations for sustainable transformation (UNESCO, 2023).

Building on these perspectives, several defining characteristics of educational ecosystems can be identified. First, they are inherently interdependent, with stakeholders continuously influencing one another (Jackson, 2013). Second, they are increasingly data-informed, with decision-making processes guided by analytics and evidence-based governance (Bates & Sangrà, 2020). Third, digital technologies enable personalized learning pathways, allowing learners to actively shape their educational trajectories in accordance with their needs and contexts (Redecker, 2017). Finally, these ecosystems rely on continuous feedback mechanisms, where learning outcomes inform ongoing pedagogical and institutional adaptation (Siemens, 2013).

A key theoretical implication of this evolution is the reconceptualization of universities as learning organizations. Senge (2006) argues that institutions must develop capacities for continuous reflection, adaptation, and knowledge renewal. Within digital ecosystems, these capacities are operationalized through the integration of governance, technology, and human agency. Personalization thus emerges not only as a pedagogical strategy but as a systemic principle, encompassing differentiated learning experiences as well as context-sensitive institutional practices (Redecker, 2017).

2.2. Current Situation in Vietnam

In recent years, Vietnam has made significant progress in advancing digital transformation in education. This progress is evident in the expansion of digital infrastructure, the increasing use of online learning platforms, and the development of national policy frameworks aligned with broader socio-economic transformation goals (Prime Minister of Vietnam, 2020; Ministry of Education and Training, 2022).

However, closer examination reveals that the development of digital education ecosystems in Vietnamese higher education remains uneven and structurally constrained.

First, digital transformation is often implemented in a fragmented manner. While many universities have adopted digital tools such as learning management systems and online teaching platforms, these technologies frequently operate as standalone solutions rather than as components of an integrated ecosystem (Dang & Pham, 2022). This limits their effectiveness and reduces opportunities for systemic innovation.

Second, data-driven governance remains underdeveloped. Although digital platforms generate substantial amounts of data, these resources are not consistently leveraged for strategic planning or decision-making. As highlighted in the OECD Digital Education Outlook, the absence of integrated data systems constrains evidence-based management in many emerging education systems (OECD, 2021).

Third, linkages among key stakeholders—including universities, industry partners, and policymakers—are relatively weak. Existing collaborations tend to be short-term and project-based, lacking the structural integration necessary for sustained ecosystem development (Tran & Nguyen, 2021). This constrains knowledge exchange, innovation capacity, and alignment with labor market demands.

Fourth, digital competencies among educators and administrators vary considerably. Despite ongoing professional development efforts, the adoption of digital pedagogies and data-informed practices remains inconsistent (Redecker, 2017; Ministry of Education and Training, 2022). Importantly, digital competence extends beyond technical skills to include pedagogical, evaluative, and collaborative dimensions.

Fifth, and perhaps most critically, personalization remains limited within current educational practices. Many institutions continue to rely on standardized curricula and delivery models, with insufficient flexibility to accommodate diverse learner needs (UNESCO, 2023). This stands in contrast to the foundational principle of digital education ecosystems, which emphasize adaptability and learner-centered design.

Taken together, these challenges indicate that Vietnam's higher education system is in a transitional phase—from digitalization, focused primarily on technology adoption, toward genuine digital transformation, which requires deeper organizational, cultural, and systemic change (OECD, 2021). However, the absence of an integrated ecosystem perspective continues to constrain this transition.

From a practice-informed standpoint, the central issue is not technological capacity, but the need to reconceptualize higher education as a personalized, interconnected, and continuously evolving ecosystem. Achieving this shift requires changes not only in infrastructure, but also in institutional mindset, governance approaches, and the role of human actors as active drivers of transformation (Senge, 2006).

3.Discussion: Integrating Theory and Practice

The juxtaposition of global theoretical frameworks and the current realities of Vietnamese higher education reveals a persistent and structurally embedded gap. While international scholarship consistently conceptualizes educational ecosystems as holistic, adaptive, and interconnected systems (OECD, 2021; UNESCO, 2023), the implementation landscape in Vietnam remains largely fragmented, with digital transformation often confined to discrete technological interventions rather than systemic reconfiguration.

This discrepancy is not incidental but reflects deeper structural and epistemic constraints that shape institutional behavior and policy enactment.

3.1. Structural Misalignment

A fundamental limitation lies in the lack of alignment between policy frameworks, institutional strategies, and technological investments. Although national policies have articulated ambitious goals for digital transformation, their translation into institutional practice is frequently uneven and uncoordinated. Universities tend to adopt digital tools—such as learning management systems or administrative platforms—without embedding them within an integrated governance architecture.

From a systemic perspective, this results in what Bates and Sangrà (2020) describe as "technology-rich but system-poor" environments, where digital resources exist but fail to generate transformative impact. The absence of interoperability among data systems further constrains the development of data-driven governance, limiting the capacity of institutions to make informed, strategic decisions.

3.2. Human Factor Constraints

A second critical issue concerns the underestimation of the human dimension in digital transformation processes. In many cases, digitalization is approached primarily as a technical challenge, focusing on infrastructure deployment rather than human capability development.

However, as emphasized in the work of Christine Redecker (2017), digital competence in education encompasses not only technical proficiency but also pedagogical innovation, assessment literacy, and collaborative knowledge construction. The uneven development of these competencies among educators and administrators significantly affects the effectiveness of digital initiatives.

Drawing on long-term engagement in teacher education and educational research, it becomes evident that sustainable transformation depends on the agency of educators as reflective practitioners. Without their active participation, digital systems risk becoming procedural tools rather than catalysts for pedagogical innovation.

3.3. Absence of Personalization

A particularly critical limitation lies in the insufficient integration of personalization within current educational practices. Although digital technologies increasingly enable adaptive and flexible learning, many higher education institutions continue to operate within standardized curricular structures and uniform instructional models. This misalignment constrains the transformative potential of digitalization, reducing it to a matter of delivery rather than redesign.

Such practices stand in tension with contemporary educational paradigms, where personalization is widely recognized as a defining characteristic of effective learning ecosystems (Holmes et al., 2019). Importantly, personalization should not be narrowly interpreted as the customization of content for individual learners. Rather, it reflects the broader capacity of an educational system to respond adaptively to diversity—in learner profiles, institutional contexts, and developmental trajectories.

From a practitioner-researcher standpoint, personalization is more usefully understood as a multi-layered construct embedded across the entire educational ecosystem. At the learner level, it involves the creation of flexible learning pathways that accommodate differences in pace, motivation, and capability. At the level of faculty, it requires professional development approaches that are differentiated and responsive to variations in digital readiness, pedagogical beliefs, and disciplinary contexts. At the institutional level, personalization is reflected in governance structures that are sufficiently adaptive to align strategic priorities with contextual realities. At the system level, it calls for policy frameworks that balance coherence with flexibility, enabling diverse institutions to pursue context-sensitive pathways of development.

Seen in this way, personalization functions as an integrative principle that connects technology, governance, and human agency into a coherent whole. Its significance extends beyond pedagogical design to encompass the broader architecture of educational transformation. Accordingly, the future development of higher education ecosystems in Vietnam will depend not only on technological advancement, but on the extent to which personalization is meaningfully embedded across these interconnected dimensions within a genuinely human-centered reform agenda.

4. Strategic Solutions

Building on the preceding analysis, and drawing on both international policy frameworks and accumulated practitioner insight within the Vietnamese higher education context, this study

proposes five interrelated strategic directions. These are not intended as discrete interventions, but as mutually reinforcing components of a systemic transformation agenda.

4.1. Developing Integrated Data-Driven Governance Systems

A critical starting point for ecosystem-based transformation lies in the development of integrated digital governance infrastructures that enable coherent data management and informed decision-making across institutional levels. In many universities, digital systems such as LMS, MIS, and ERP platforms remain fragmented, limiting their capacity to generate actionable insights.

Addressing this fragmentation requires not only technical interoperability but also the strategic alignment of data architectures with institutional goals. Learning analytics, in particular, should be embedded within core processes—including curriculum design, student progression monitoring, and quality assurance—rather than treated as an auxiliary function. As emphasized by the Organisation for Economic Co-operation and Development (2021), data-informed governance constitutes a key mechanism through which education systems enhance adaptability and responsiveness.

However, technological integration alone is insufficient. The effectiveness of data-driven governance ultimately depends on the development of a data-literate institutional culture, in which academic leaders, administrators, and faculty are equipped to interpret, contextualize, and act upon data in meaningful ways. Without such capacity, data systems risk becoming performative tools rather than instruments of transformation.

4.2. Strengthening Digital Competencies for Educators and Administrators

The sustainability of digital transformation is fundamentally contingent upon the competencies of its human actors. While digital infrastructure provides the enabling conditions, it is the capacity of educators and administrators that determines how effectively these resources are mobilized.

Existing frameworks, such as DigCompEdu, offer valuable reference points for defining digital competence. Nevertheless, their application in the Vietnamese context requires careful adaptation to account for institutional diversity, disciplinary variation, and uneven levels of technological readiness. Professional development, therefore, should be reconceptualized as a continuous and practice-embedded process rather than a series of discrete training events.

Evidence from professional practice suggests that differentiated development pathways—tailored to varying levels of experience and confidence—are significantly more effective than standardized approaches. Moreover, meaningful competency development must extend beyond technical proficiency to include digital pedagogy, innovative assessment strategies, and collaborative knowledge-building practices. In this sense, capacity building becomes not only an individual endeavor but also an organizational learning process.

4.3. Building Multi-Stakeholder Educational Ecosystems

For higher education institutions to function effectively within contemporary knowledge societies, they must move beyond insular organizational models and actively engage with broader innovation ecosystems. This entails repositioning universities as dynamic nodes within networks that include industry, government, and community stakeholders.

The development of innovation hubs, applied research collaborations, and knowledge exchange platforms plays a crucial role in facilitating this transition. Such mechanisms not only

enhance the societal relevance of academic programs but also support the co-production of knowledge aligned with labor market and community needs (Carayannis & Campbell, 2009).

In the Vietnamese context, however, these linkages often remain ad hoc and project-based, lacking the institutional depth required for long-term impact. A key strategic priority, therefore, is the formalization and institutionalization of partnerships through governance structures, incentive systems, and sustained collaborative frameworks. Without this shift, ecosystem development risks remaining episodic rather than systemic.

4.4. Promoting Comprehensive Digital Transformation Policies

System-level transformation requires policy environments that are both coherent and forward-looking. At present, digital transformation initiatives in higher education are often characterized by partial alignment between national strategies and institutional implementation.

To address this, it is essential to develop integrated policy frameworks that connect digital infrastructure, governance mechanisms, quality assurance, and human resource development. At the same time, these frameworks must preserve institutional autonomy, allowing universities to design context-sensitive strategies rather than conform to rigid, one-size-fits-all models.

Particular attention should be given to the development of legal and regulatory frameworks for digital education, including accreditation of online learning, data governance standards, and intellectual property protections. Furthermore, issues of equity must remain central. As highlighted by UNESCO (2023), ensuring equitable access to digital resources across regions and institutional types is a prerequisite for inclusive and sustainable ecosystem development. Without such considerations, digital transformation may inadvertently exacerbate existing disparities.

4.5. Fostering Personalized and Adaptive Learning Environments

The advancement of personalized learning environments represents a pivotal dimension of educational ecosystem transformation. While emerging technologies—including artificial intelligence and learning analytics—offer powerful tools for enabling adaptive learning, their effectiveness depends on how they are pedagogically and institutionally integrated.

Personalization should not be reduced to algorithmic customization or content delivery. Rather, it requires a fundamental reorientation of curriculum design toward modularity, flexibility, and competency-based progression. Equally important is the promotion of learner agency, where students are not passive recipients of knowledge but active participants in its construction.

This shift also entails a redefinition of the educator's role—from that of a knowledge transmitter to a facilitator, mentor, and co-learner within dynamic learning processes. However, experience from practice indicates that the success of personalization is highly contingent upon its alignment with existing cultural norms, institutional structures, and pedagogical traditions. When introduced without such alignment, personalization risks becoming superficial or symbolic rather than transformative. To operationalize and systematically represent these interdependent dimensions, the following model is proposed

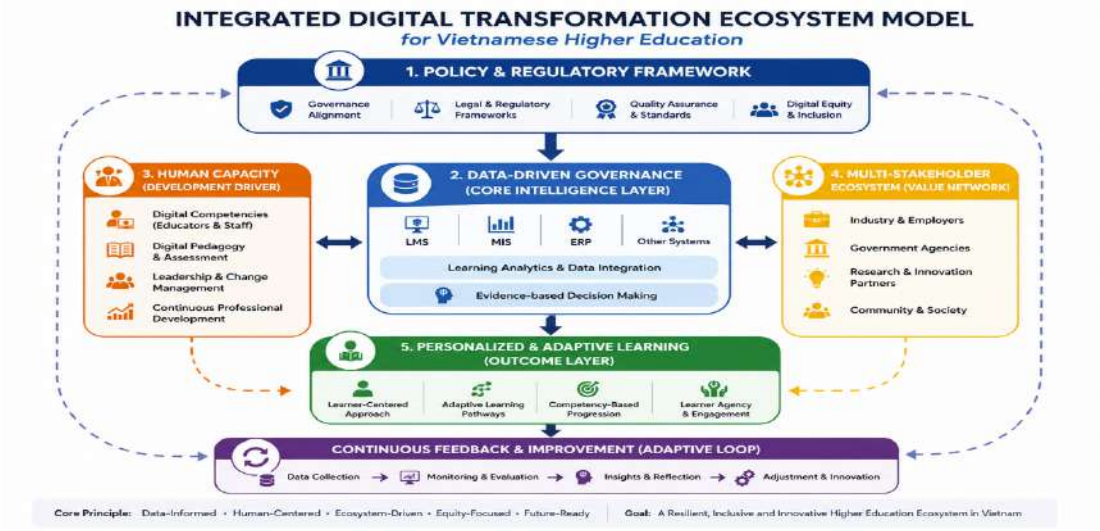


Figure 1. Integrated Digital Transformation Ecosystem Model for Vietnamese Higher Education

5. Conclusion and Recommendations

5.1. Conclusion

This study has advanced a strategic and conceptual framework for understanding educational ecosystems in Vietnamese higher education by integrating international theoretical perspectives with a context-sensitive analysis of current institutional practices. By positioning universities within a broader ecosystem paradigm, the paper moves beyond fragmented and technology-centric interpretations of digital transformation, reframing it instead as a systemic, relational, and continuously evolving process.

Three interrelated insights emerge from the analysis.

First, educational ecosystems in higher education should be understood as holistic and adaptive configurations, in which technology, governance, human resources, and socio-cultural conditions are not isolated variables but mutually constitutive elements of a coherent system. In this sense, the effectiveness of digital transformation depends less on the scale of technological investment than on the degree of alignment and integration across these dimensions.

Second, digital transformation must be approached as a process of organizational and cultural reconfiguration rather than a purely technical upgrade. This involves the development of data-informed governance practices, institutional learning capacities, and iterative feedback mechanisms that enable universities to respond proactively to evolving educational and societal demands (OECD, 2021; Bates & Sangrà, 2020). Without such shifts, digital initiatives risk remaining operational rather than transformative.

Third, and most significantly, the study underscores personalization as a central organizing principle of contemporary educational ecosystems. However, personalization should not be narrowly interpreted as individualized learning facilitated by digital tools. Drawing on long-term engagement in educational research and teacher development, this study argues that personalization must be conceptualized as a systemic principle that informs multiple levels of the educational structure, including: (1) the design of flexible and learner-responsive curricula, (2) the development of differentiated and context-sensitive professional pathways for educators,

and (3) the construction of adaptive governance models capable of responding to institutional diversity.

Understood in this way, personalization is not simply a pedagogical innovation but a strategic and organizational imperative for higher education reform in Vietnam.

5.2. Recommendations

Building on these findings, several implications can be drawn for key stakeholders involved in higher education transformation.

For policymakers, the priority lies in developing integrated national frameworks for digital education ecosystems. Such frameworks should move beyond fragmented sectoral policies and instead establish coherent linkages among data governance, quality assurance, digital infrastructure, and human resource development. At the same time, policy design must allow for contextual flexibility, enabling institutions to adapt strategies in accordance with their specific conditions rather than imposing uniform implementation models.

For universities, the central challenge is to transition from isolated digital initiatives toward ecosystem-based governance. This requires the integration of digital platforms into unified data architectures, the adoption of evidence-informed decision-making processes, and the strengthening of institutional capacities for strategic coordination. Equally important is the cultivation of internal cultures that value collaboration, knowledge sharing, and continuous improvement, as these are essential conditions for sustaining ecosystem dynamics over time.

For educators, meaningful transformation depends on a shift toward continuous professional learning and pedagogical innovation. Digital competence should be understood as a dynamic and evolving capacity that integrates technological, pedagogical, and evaluative dimensions. Professional development, therefore, needs to move beyond standardized training models and instead support differentiated learning trajectories that reflect variations in experience, readiness, and disciplinary context.

For researchers, the findings point to the need for further empirical and conceptual work on ecosystem-based approaches to education, particularly in emerging and transitional contexts such as Vietnam. Future research should extend beyond questions of technological adoption to examine issues of governance, institutional culture, and human agency, as well as the conditions under which personalization can be meaningfully implemented at scale.

5.3. Final Reflection

From a cumulative research and practice perspective, the transformation of higher education in Vietnam cannot be achieved through structural reform alone. More fundamentally, it requires the gradual cultivation of a learning-oriented academic culture in which institutions, educators, and learners engage in continuous processes of reflection, adaptation, and knowledge co-construction.

Within this evolving landscape, personalization should be understood not as an optional feature but as a guiding principle that connects individual development with institutional transformation. Only when educational ecosystems are designed to acknowledge and respond to the diversity of human experiences can digital transformation move beyond procedural compliance and become a substantive driver of educational quality, innovation, and social progress.

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THE EFFECTS OF SHADING ON FIBER YIELD AND FIBER QUALITY IN COTTON

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ABSTRACT

Cotton is an important fiber crop that provides raw materials to the textile industry and is produced in more than 80 countries worldwide. Due to its climate-selective nature, cotton can only be grown in limited areas in Turkey. High temperature stress negatively affects productivity in cotton production areas. The most effective method to address this stress factor is to develop high-temperature tolerant cotton varieties. However, some innovative agricultural approaches are also gaining interest in order to reduce or mitigate the negative effects of the expected increase in high temperatures in the future. One of these is investigating the effect of shading to reduce the impact of high temperatures. This research was conducted to determine the effects of shading on fiber yield and fiber quality in 5 different cotton (*Gossypium hirsutum* L.) varieties grown under normal growth and 30% shading conditions. In the experiment, 5 cotton varieties (DP 499, Stoneville 468, Stoneville 498, MAY 455, MAY 558) and black shade netting providing 30% shade were used. The study revealed statistically significant differences in fiber yield between normal and shading conditions, with shading causing a 26.66% decrease in fiber yield. Fiber cotton yield was found to be 158.99 kg da^{-1} under normal growing conditions and 118.19 kg da^{-1} under shading conditions. Shading did not significantly affect fiber quality criteria; however, the percentage of short fibers increased with shading, and the application x variety interaction was significant for fiber uniformity. The study also determined that variety differences were significant in terms of fiber quality traits except fiber length and uniformity. For future research, it is recommended to apply shading for short periods at different stages of plant development and to use light-colored shade netting.

Keywords: Shading, Cotton, High Temperature, Variety, Fiber Quality

PAMUKTA GÖLGELEMENİN LİF VERİMİ VE LİF KALİTESİNE ETKİSİNİN BELİRLENMESİ

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ÖZET

Pamuk tekstil sektörüne hammadde sağlayan önemli bir lif bitkisi olup, Dünya'da 80'den fazla ülkede üretimi yapılmaktadır. Pamuk iklim bakımından seçici bir bitki olması nedeni ile ülkemizde sınırlı alanlarda yetiştirilebilmektedir. Pamuk üretim alanlarında yüksek sıcaklık stresi verimliliği olumsuz etkilemektedir. Bu stres faktörüne çözüm olabilecek en etkili yöntem yüksek sıcaklığa tolerant pamuk çeşitlerini geliştirmektir. Ancak gelecekte artacağı beklenen yüksek sıcaklıkların olumsuz etkilerini azaltmak veya hafifletebilmek amacıyla bazı yenilikçi tarımsal yaklaşımlarda ilgi görmektedir. Bunlardan biri de yüksek sıcaklığın etkisini azaltabilmek adına gölgelemenin etkisini araştırmaktır. Bu araştırma normal gelişme ve %30 gölgeleme koşullarında yetiştirilen 5 farklı pamuk (*Gossypium hirsutum L.*) çeşidinde gölgelemenin lif verimine ve lif kalitesine olan etkilerini belirlemek amacıyla yürütülmüştür. Denemede 5 pamuk çeşidi (DP 499, Stoneville 468, Stoneville 498, MAY 455, MAY 558) ve %30 gölge sağlayan siyah renkte gölge tülü materyal olarak kullanılmıştır. Araştırmada normal ve gölgeleme koşullarında lif verimi bakımından önemli istatistiki farklılıkların bulunduğu, gölgelemenin lif veriminde %26,66 oranında azalışa yol açtığı belirlenmiştir. Normal gelişme koşullarında lif pamuk veriminin 158,99 kg da^{-1}, gölgeleme koşullarında ise 118,19 kg da^{-1} olduğu tespit edilmiştir. Gölgelemenin lif kalite kriterlerine önemli bir etkisinin olmadığı, kısa lif oranının gölgeleme ile arttığı, lif üniformite oranında ise uygulama x çeşit interaksiyonunun önemli olduğu tespit edilmiştir. Çalışmada lif uzunluğu ve üniformite hariç lif kalite kriterleri bakımından çeşit farklılıklarının önemli olduğu belirlenmiştir. Yapılacak araştırmalarda bitki gelişiminin farklı dönemlerinde gölgelemenin kısa süreli olarak yapılması ve açık renkli gölge tülünün kullanılması önerilmektedir.

Anahtar Kelimeler: Gölgeleme, Pamuk, Yüksek Sıcaklık, Çeşit, Lif Kalitesi

1. Introduction

Cotton is an important fiber crop that provides raw materials to the textile industry and is produced in more than 80 countries worldwide. Due to its climate-selective nature, cotton can only be grown in limited areas in Türkiye. High temperature stress negatively affects productivity in cotton production areas. The most effective method to address this stress factor is to develop high-temperature tolerant cotton varieties. However, some innovative agricultural approaches are also gaining interest in order to reduce or mitigate the negative effects of the expected increase in high temperatures in the future. One of these is investigating the effect of shading to reduce the impact of high temperatures. Many factors affect crop productivity. One of the most important factors affecting yield is climate parameters. Rising temperatures and changes in rainfall patterns have the greatest impact on the agricultural sector. For every 1°C increase in the daily maximum temperature, fiber yield decreases by 11 kg da^{-1} (Singh et al., 2007). Consequently, a strong and negative relationship between high temperature and fiber yield has been proven. To maintain fiber yield potential without compromising quality under high temperature stress, it is essential to understand the effects of heat stress on various stages of plant growth and development and the associated tolerance mechanisms (Saini et al., 2023). In addition to the negative effects of high temperatures on cotton, low temperatures and low light levels in many cotton-growing areas also negatively affect boll development and reduce fiber quality. Light, temperature, and humidity are essential factors for plant growth. Sunlight is one of the most important factors affecting cotton yield and quality. Light is a fundamental environmental factor necessary for plant growth and development; however, plants are affected not only by the amount of light but also by the quality of light, such as light and radiation at different wavelengths and compositions (Chen et al., 2019).

Appropriate light intensity is fundamental for optimal plant growth and development. Exposure to high-intensity light can lead to excessive light energy, thus reducing photochemical efficiency in plants. It has been reported that field-grown cotton is negatively affected by low light conditions during the flowering and boll formation periods (Shu et al., 2009). Brown clouds, which also lead to a significant reduction in radiation, cause approximately a 40% decrease in ultraviolet and visible wavelengths (Ramanathan and Feng, 2009). Both of these factors lead to a decrease in photosynthetically active radiation (PAR) and have a major impact on cotton production in many countries due to air pollutants and overcast weather that frequently occur during the cotton growing season (Zhao and Oosterhuis, 1998a; Yan et al., 2007).

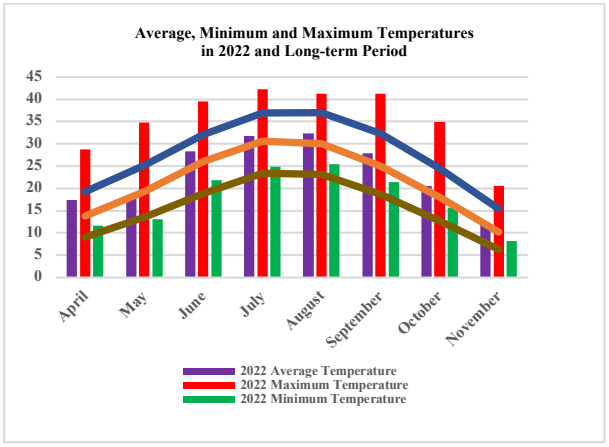
Although the effects of shading on cotton yield have been reported in previous studies, there appears to be insufficient information and clarity regarding the timing and duration of shading during the cotton growing season, its effects on plant physiological reactions, yield responses, and fiber quality (Wang et al., 2006). However, the response of fiber quality to shading has not been definitively determined due to the timing and duration of shading (Zhao and Oosterhuis, 1996). Sorour and Rassoul (1974) reported that shading cotton plants at the onset of flowering resulted in a decrease in flowering and complete boll shedding compared to continuous shading. Shading applied 3 weeks before the start of flowering increased the number of flowers, but increased the percentage of boll shedding and decreased the number of bolls and cotton yield. Zhao and Oosterhuis (1998a) reported that shading for 8 days during the early squaring stage did not significantly affect cotton growth and yield, but shading during flowering and fruiting significantly increased fruit drop, reduced fiber yield and fiber quality. Chen et al.

(2017) reported that the number and mass of cotton bolls decreased with shading, but fiber strength, fiber fineness and fiber length increased.

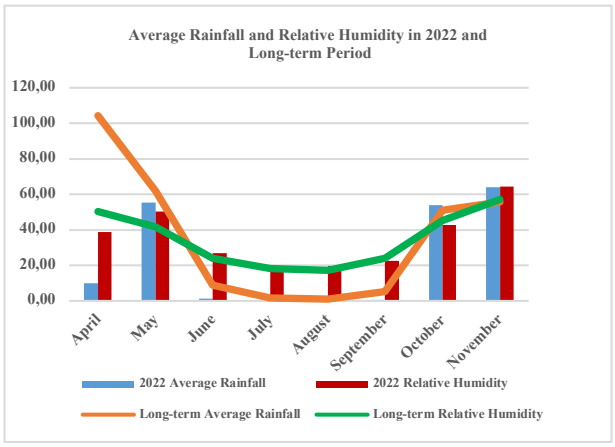
This study was conducted to determine the effectiveness of shading in identifying or mitigating the effects of climate change and rising temperatures on cotton production, and to determine the effects of normal growing and shading conditions on cotton fiber yield and fiber quality.

2. Material and Methods

This study was conducted at the experimental field of the Faculty of Agriculture, Siirt University in 2022. Five cotton varieties (DP 499, Stoneville 468, Stoneville 498, MAY 455, MAY 558) were used as material. The cotton varieties were sown at the normal planting time, and their growth was comparatively examined under normal conditions and under shade using a 30% shade net. The experiment was established in a split-plot design with four replications. Two growing conditions (normal and shade) were assigned to the main plots, while five cotton varieties were used as subplots. The area to be shaded was covered with 30% shade netting, stretched over 2,5 m long pine poles using steel tension wire. For this process, the poles were first driven into the ground in the test area. To reduce the effect of the sun, a shade net has been placed at the top (Figure 1 and Figure 2). Sowing in the experiment was carried out on May 13, 2022, using a precision drill. During planting preparation in the experimental area, soil samples were taken from a depth of 0-30 cm from the soil surface, and some soil properties and nutrient element content were determined. The soil in the experimental area was determined to have a clayey and slightly alkaline, low electrical conductivity, low lime content and nitrogen, very low organic matter and available phosphorus and sufficient available potassium. Climate data for 2022, the year the experiment was conducted, and for long term periods are given in Graphics 1 and Graphics 2.



Graphics 1. Average, minimum and maximum temperature in 2022 and long-term perios



Graphics 2. Average rainfall and relative humidity in 2022 and long-term period

Each plot consisted of four rows, each 6 m in length, with a total plot area of 16.8 m². Row spacing was 70 cm at sowing, and plants were thinned to 15-20 cm within rows. Each plot was 2.8 m wide, and blocks were separated by 2 m. Shading was started at the beginning of flowering and continued until the end of the boll ripening period.



Figure 1. Shading conditions



Figure 2. Cotton growing under shading

2.1. Cultural Management

The experiment was conducted using a drip irrigation system. Irrigation was started 40-45 days after planting (the squaring stage) and completed when 10% of the bolls had opened. A total of 14 kg da^{-} of pure nitrogen and 8 kg da^{-1} of pure phosphorus were applied to the experiment. Harvesting was done by hand in the middle two rows of the four-row plots, and the total yield per hectare was then calculated. The first-hand harvest was performed when at least 60% of the bolls had opened, and the remaining product was collected in the second-hand harvest.

2.2. Data Collection and Measurement

Fiber yield obtained from each plot was weighed, and yield per plot was calculated and expressed as kilogram per decare (kg da^{-1}) and fiber technological analyses were determined in the fiber quality laboratory of the GAP International Agricultural Research and Training Center using the HVI 1000 instrument.

2.3. Statistical Analysis

All data obtained from the experiment were analyzed using the JUMP statistical package program, in accordance with the experimental design used. Groupings were made according to $LSD_{(0.05)}$.

3. Results and Discussion

In the study, the results of the variance analysis for the investigated traits, mean of squares and LSD $_{(0.05)}$ test are presented in Table 1a and Table 1b. It can be seen from the Table that shading had significant effect on fiber yield and short fiber index, however shading had no significant effect on fiber fineness, fiber length, fiber strength, and fiber elongation, variety differences were also significant for fiber fineness, fiber strength, elongation, short fiber index, reflectance, yellowness and spinning consistency index.

Table 1a. Analysis of variance for fiber yield and fiber quality parameters

Source of Variation	DF	Fiber Yield	Fiber Fineness	Fiber Length	Fiber Strength	Fiber Elongation
Model	15	1235,93	0,06	1,12	7,54	0,26
Replication	3	50,71	0,02	3,11	13,71	0,17
Treatment	1	16644,80**	0,001	0,003	0,03	1,26
ReplicationxTreatment&Random	3	170,07	0,03	1,22	1,09	0,12
Variety	4	201,72	0,18*	0,91	14,33**	0,39**
Treatment x Variety	4	106,19	0,01	0,05	2,85	0,03
Error	24	312,54	0,04	0,79	2,83	0,06
General	39					

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

Table 2b. Analysis of variance for fiber quality parameters

Source of Variation	F	Fiber Uniformity	Short Fiber Index	Fiber Reflectance	Fiber Yellowness	Spinning Consistency Index
Model	5	3,53	5,91	5,30	0,31	302,81
Replication		9,03	14,87	0,58	0,03	689,62
Treatment		6,72	17,29**	6,56	0,13	235,22
ReplicationxTreatment&Random		1,03	0,30	2,40	0,06	84,09
Variety		1,13	5,26*	15,77**	1,00**	331,31*
Treatment x Variety		2,87*	1,19	0,21	0,06	165,16
Error	4	0,91	1,42	1,88	0,15	114,00
General	9					

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

The findings regarding fiber yield and fiber quality criteria of 5 cotton varieties (DP 499, Stoneville 468, Stoneville 498, MAY 455, MAY 558) grown under normal growth and shading conditions are shown in the tables. The mean values of fiber yield under normal growing conditions and shading conditions and the groupings formed according to the LSD $_{(0.05)}$ test are given in Table 2. It can be seen that there are statistically significant differences at the 1% significance level between the treatments in terms of fiber yield, while the variety and treatment x variety interaction is not significant.

Table 2. Average fiber yield and fiber fineness values of cotton varieties under normal and shading conditions

	Fiber Yield (kg da^{-1})			Fiber Fineness (mic.)		
	Treatment		Average	Treatment		Average
Variety	**Normal**	**Shading**		**Normal**	**Shading**	
1. DP 499	159,61	120,19	139,90	4,80	4,88	4,84 ab
2. Stv 468	160,29	130,21	145,25	4,71	4,65	4,68 bc
3. Stv 498	156,33	106,07	131,20	4,99	4,91	4,95 a
4. MAY 455	159,87	116,58	138,23	4,57	4,60	4,58 c
5. MAY 558	158,85	117,91	138,38	4,59	4,66	4,62 bc
Average	**158,99 a**	**118,19 b**	**138,59**	**4,73**	**4,74**	**4,73**
CV (%)	12,74			4,5		
LSD $_{(0.05)}$ Treatment	13,10**			ns		
LSD $_{(0.05)}$ Variety	ns			0,220*		
LSD $_{(0.05)}$ T x V	ns			ns		

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

Table 2 shows that under normal growing conditions, the fiber yield was 158.99 kg da^{-1}, while under shading conditions it was 118.19 kg da^{-1}, indicating a statistically significant difference at the 1% significance level between the two treatments. When cotton varieties were grown under shading conditions, there was a decrease in fiber yield compared to normal growing conditions, and this decrease was 25.66%. The fiber yield obtained from the cotton varieties was found to range between 131.20 and 145.25 kg da^{-1}. Although there was no statistically significant difference between the varieties, the highest fiber yield was obtained from the STV 468 variety (145.25 kg da^{-1}), and the lowest yield was obtained from the STV 498 variety (131.20 kg da^{-1}). Zhao and Oosterhuis (1998a) reported that 8 days of shading during the early squaring period (under conditions where light was reduced by 63%) did not affect fiber yield, but shading during flowering and fruiting led to a decrease in fiber yield. Similar results were obtained in this study. Lv et al. (2013) stated that shading reduced the number of bolls and boll weight, leading to a decrease in fiber yield.

Statistically significant differences at the 5% significance level were found between varieties in terms of fiber fineness (Table 2). The highest fiber fineness was obtained from the STV 498 variety (4.95 mic.), and the lowest fiber fineness value was obtained from the MAY 455 variety (4.58 mic.). It was determined that the application x variety interaction was not significant in terms of fiber fineness. Zhao and Oosterhuis (1998b) reported that, among the five important cotton fiber quality characteristics, fiber fineness is the most sensitive to shade during flowering and fruiting, and that shading during boll development significantly reduces the fiber micronaire value. Echer (2017) expressed similar findings regarding the decrease in fiber fineness with shading. Lv et al. (2013) reported that shading is advantageous for fiber fineness, Wang et al. (2005) reported that shading decreases fiber thickness, and Chen et al. (2017) reported that shading increases fiber fineness. On the other hand, Raphael et al., 2024 revealed that shading had no significant effect on fiber micronaire. It is observed that different results were obtained in this study and that different findings were also obtained in the literature.

Table 3 shows that there is no statistically significant difference in fiber length between the treatments. Under normal growing conditions, the average fiber length of the cotton varieties included in the experiment was 27.99 mm, while under shading conditions, the fiber length was 28.00 mm. It was observed that shading conditions did not have a significant effect on fiber length.

The fiber length values of the cotton varieties ranged from 27.50 to 28.42 mm. Although there was no statistically significant difference between the varieties, the highest fiber length was obtained from the STV 468 variety (28.42 mm), and the lowest value was obtained from the MAY 558 variety (27.50 mm). The study results differ from those of Liu et al. (2015a), who reported that fiber length increased with shading, Lv et al. (2013), who found that shading was advantageous for fiber length, and Wang et al. (2005), who reported that fiber length decreased with shading. Similar results were obtained with the findings of Zhao and Oosterhuis (2000) and Raphael et al. (2024), who reported that fiber length was not affected by shading. Chen et al. (2014) revealed that shading was disadvantageous in terms of fiber length if planting was delayed, and that low light negatively affected fiber length.

Table 3. Average fiber length and fiber strength values of cotton varieties under normal and shading conditions

	Fiber Length (mm)			**Fiber Strength (g tex^{-1})**		
	Treatment		**Average**	**Treatment**		**Average**
Variety	**Normal**	**Shading**		**Normal**	**Shading**	
1. DP 499	28,10	28,22	28,16	32,45	32,62	32,53 a
2. Stv 468	28,32	28,52	28,42	31,27	31,00	31,13 ab
3. Stv 498	27,88	27,98	27,93	28,45	29,60	29,02 c
4. MAY 455	28,07	27,90	27,98	30,50	31,12	30,81 ab
5. MAY 558	27,57	27,42	27,50	30,80	28,82	29,81 bc
Average	**27,99**	**28,00**	**27,99**	30,69	30,63	30,66
CV (%)	3,17			5,47		
LSD $_{(0.05)}$ Treatment	ns			ns		
LSD $_{(0.05)}$ Variety	ns			1,73**		
LSD $_{(0.05)}$ T x V	ns			ns		

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

Table 3 shows that the average fiber strength of the cotton varieties included in the experiment under normal growing conditions was 30.69 g tex^{-1}, while under shading conditions the fiber strength was 30.63 g tex^{-1}; however, the difference between the treatments was not statistically significant. It was determined that there was no statistically significant difference in fiber strength between normal growing and shading conditions. It was observed that the fiber strength value did not change when cotton varieties were grown under shading conditions, and shading did not have a significant effect.

It can be seen that from the same Table, there are statistically significant differences at the 1% significance level among the varieties in terms of fiber strength. The fiber strength values of the cotton varieties ranged from 29.02 to 32.53 g tex^{-1}, with the highest fiber strength value obtained from the DP 499 variety (32.53 g tex^{-1}) and the lowest fiber strength obtained from the STV 498 variety (29.02 g tex^{-1}). While Liu et al. (2015a) reported that fiber strength decreased with shading, and Zhao and Oosterhuis (2000) reported that fiber strength decreased, Lv et al. (2013) reported that shading was disadvantageous for fiber strength. The findings of Chen et al. (2017), who reported that fiber strength increased with shading, differ from the results of this study.

It was determined that there was no statistically significant difference between normal growth conditions and shading conditions in terms of fiber elongation. Table 4 shows that the average values for fiber elongation of the cotton varieties included in the experiment under normal growth conditions were 5.52%, while under shading conditions was 5.87%. It was

observed that shading did not have a significant effect on fiber elongation. It can be observed that the treatment and treatment x variety interaction is not statistically significant in terms of fiber elongation, while statistically significant differences at the 1% significance level were determined between varieties. The highest fiber elongation value was observed from Stv 468 and the lowest value was observed from the Stv 498. Zhou et al. (2002) confirmed these findings who revealed that different cotton varieties were different in their shade-tolerance, according to comprehensive analysis of the yield and quality formation.

Table 4. Average fiber elongation and fiber üniformity values of cotton varieties under normal and shading conditions

	Fiber Elongation			**Fiber Uniformity (%)**		
	Treatment		**Average**	**Treatment**		**Average**
Variety	**Normal**	**Shading**		**Normal**	**Shading**	
1. DP 499	5,45	5,92	5,68 a	84,32 a	82,82 bcd	83,57
2. Stv 468	5,82	6,00	5,91 a	83,87 ab	83,00 abcd	83,43
3. Stv 498	5,07	5,57	5,32 b	82,35 cd	83,55 abc	82,95
4. MAY 455	5,62	5,97	5,80 a	83,17 abcd	82,15 d	82,66
5. MAY 558	5,62	5,90	5,76 a	83,92 ab	82,02 d	82,97
Average	**5,52**	**5,87**	**5,69**	**83,53**	**82,71**	**83,12**
CV (%)	**4,57**			**1,14**		
LSD $_{(0.05)}$ Treatment	ns			ns		
LSD $_{(0.05)}$ Variety	0,27**			ns		
LSD $_{(0.05)}$ T x V	ns			1,39*		

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

The mean values of the fiber uniformity ratio of the varieties under normal growth conditions and shading conditions and the groupings formed according to the LSD $_{(0.05)}$ test are given in Table 4. It can be seen from the Table 4 that the application and variety differences is not statistically significant in terms of fiber uniformity, but the application x variety interaction is significant at the 5% level. It can be seen from the same Table that the average values of the fiber uniformity ratio of the cotton varieties in the experiment under normal growth conditions are 83.53%, and under shading conditions the fiber uniformity ratio are 82.71%, but the differences between the applications is not significant.

The treatment x variety interaction was found to be significant in the fiber uniformity. The highest value was obtained from the DP 499 variety (84.32%) under normal growing conditions, while the lowest value was obtained from the MAY 558 variety (82.02%) under shading conditions. The significant finding of the treatment x variety interaction indicates that the fiber uniformity ratio of the varieties may change depending on whether they are grown under normal growing and shading conditions. The fiber uniformity ratio of the cotton varieties included in the experiment ranged from 82.66% to 83.57%, and no significant difference was determined between the varieties in terms of this characteristic. The findings of Zhao and Oosterhuis (2000), who reported that other fiber quality characteristics besides fineness and length were not affected by shading, show similarity with the results of this research.

Statistically significant differences were found between treatments at the 1% level and between varieties at the 5% significance level in terms of short fiber index, while the treatment x variety interaction was not statistically significant. The average short fiber ratio of cotton varieties in the experiment under normal growth conditions was 8.34%, while under shading conditions it was 9.65%. Shading conditions were in group A, while normal growth conditions were in group B. Cotton varieties produced 15.70% more short fibers when grown under shading conditions.

Table 5. Average short fiber index and fiber reflectance values of cotton varieties under normal and shading conditions

	Short Fiber Index			Fiber Reflectance		
	Treatment		Average	Treatment		Average
Variety	**Normal**	**Shading**		**Normal**	**Shading**	
1. DP 499	7,17	8,35	7,76 b	80,42	79,80	80,11 a
2. Stv 468	8,20	9,10	8,65 ab	78,40	78,02	78,21 b
3. Stv 498	8,95	9,57	9,26 a	78,40	77,15	77,77 bc
4. MAY 455	8,87	10,12	9,50 a	77,15	76,20	76,67 c
5. MAY 558	8,50	11,12	9,81 a	77,15	76,30	76,72 c
Average	**8,34 b**	**9,65 a**	**8,99**	**78,30**	**77,49**	**77,89**
CV (%)	0,13			1,76		
LSD $_{(0.05)}$ Treatment	0,57**			ns		
LSD $_{(0.05)}$ Variety	1,22*			0,59 **		
LSD $_{(0.05)}$ T x V	ns			ns		

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

The short fiber index values of the cotton varieties in the experiment ranged from 7.76% to 9.81%. The highest short fiber index was obtained from MAY 558 (9.81%), MAY 455 (9.50%), and STV 498 (9.26%) varieties, while the lowest short fiber ratio was obtained from DP 499 (7.76%). While Echer (2017) reported that the short fiber index value showed similar values in cotton plants grown under shading and normal conditions, Zhao and Oosterhuis (2000) reported that other fiber quality characteristics besides fineness and length were not affected by shading, indicating a difference in research results. Raphael et al. (2024) found that the short fiber ratio was rarely affected by shading, showing a partial similarity to this research results.

Table 5 shows that there are statistically significant differences were found between varieties in terms of fiber reflectance at the 1% significance level, while the treatment and treatment x variety interaction was not significant. The average fiber reflectance of the cotton varieties under normal growing conditions was 78.30, while under shading conditions the fiber reflectance was 77.49. It was determined that shading has no significant effect on fiber reflectance. Statistically significant differences at the 1% significance level were found among the varieties, fiber reflectance values of the cotton varieties ranged from 76.67 to 80.11. The highest value was obtained from the DP 499 variety (80.11) and the lowest values were obtained from the MAY 455 (76.67) and MAY 558 (76.72) varieties. The findings of Zhao and Oosterhuis (2000), who reported that other fiber quality characteristics besides fineness and length were not affected by shading, show similarity to the results of this research.

Statistically significant differences were found between varieties in terms of fiber yellowness at the 1% significance level, while the treatment and treatment x variety interaction was not statistically significant. Table 6 shows that although there is no statistically significant difference between the treatments, the average fiber yellowness value of the cotton varieties under normal growth conditions is 9.19, while the fiber yellowness value under shading conditions is 9.07. It has been determined that there is no statistically significant difference in fiber yellowness value when cotton varieties are grown under shading conditions.

It was observed that there were statistically significant differences at the 1% significance level among the varieties in terms of this characteristic, that the fiber yellowness values of the cotton varieties ranged from 8.55 to 9.46, that the highest values were obtained from STV 468, MAY 455, MAY 558 and STV 498 varieties and that these varieties shared same group, and

that the lowest value was obtained from DP 499 variety. The research results appear to be similar to the findings of Zhao and Oosterhuis (2000), who reported that other fiber quality characteristics besides fineness and length were not affected by shading.

Table 6. Average short fiber index and SCI of cotton varieties under normal and shading conditions

	Fiber Yellowness			Spinning Consistency Index (SCI)		
	Treatment		Average	Treatment		Average
Variety	**Normal**	**Shading**		**Normal**	**Shading**	
1. DP 499	8,52	8,57	8,55 b	144,25	136,50	140,37 a
2. Stv 468	9,57	9,35	9,46 a	139,00	134,25	136,62 ab
3. Stv 498	9,25	8,92	9,08 a	119,75	128,75	124,25 c
4. MAY 455	9,42	9,25	9,33 a	133,25	128,75	131,00 abc
5. MAY 558	9,17	9,27	9,22 a	136,50	120,25	128,37 bc
Average	**9,19**	**9,07**	**9,13**	**134,55**	**129,70**	**132,12**
CV (%)	4,27			18,83		
LSD $_{(0.05)}$ Treatment	ns			ns		
LSD $_{(0.05)}$ Variety	0,40**			11,01 *		
LSD $_{(0.05)}$ T x V	ns			ns		

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

Statistically significant differences were found between varieties at the 5% significance level in terms of the spinning consistency index (SCI), while the treatment and treatment x variety interaction were not significant (Table 6). The SCI values of the cotton varieties ranged from 124.25 to 140.37, the highest value was obtained from the DP 499 variety (140.37), and the lowest value was obtained from the STV 498 variety (124.25). It has been observed that growing cotton varieties under shading conditions does not have a significant effect on the spinning consistency index. The research results appear to be similar to the findings of Zhao and Oosterhuis (2000), who reported that fiber quality characteristics were not affected by shading.

4. Conclusion

It was determined that fiber yield values decreased with shading. Fiber yield was 158.99 kg da^{-1} under normal growth conditions and 118.19 kg da^{-1} under shading conditions, indicating a 26.66% decrease in fiber yield with shading. It was determined that shading did not have a significant effect on fiber quality criteria such as fiber fineness, fiber length, fiber strength, elongation, yellowness, reflectance, and spinning consistency index; however, it increased the short fiber ratio, and the treatment x variety interaction was found to be significant in terms of fiber uniformity. Significant differences were found among the varieties in terms of fiber fineness, fiber strength, fiber elongation, short fiber index, fiber reflectance, fiber yellowness, and spinning consistency index. DP 499 variety was found to be superior in terms of quality characteristics. In the study, shading was provided with shade netting that provided 30% shade, and a 25% loss in fiber yield was observed. Shading was applied from the beginning of flowering to the boll maturation period. It is recommended that future studies use lighter-colored shade netting for shorter periods and compare results obtained at different times. More reliable recommendations can only be made after at least two years of research.

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THE EFFECTS OF ASCORBIC ACID ON PLANTS

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ABSTRACT

Improving plant growth and productivity under optimal conditions is one of the most fundamental goals of current agricultural production. However, plant production is negatively affected by abiotic stress conditions. Global climate change leads to a number of environmental stresses in plants, such as low and high temperatures, drought, salinity, radiation, and heavy metal stress. Ascorbic acid (AsA) promotes a range of beneficial effects on plant development, primarily by functioning as a key regulator of defense mechanisms under adverse abiotic stress conditions. Ascorbic acid (ascorbate/AsA/vitamin C) acts as an important antioxidant and enzyme cofactor in plants. AsA is a significant antioxidant in combating oxidative stress in plants. It regulates various physiological processes, including growth, development, and signal transduction, as well as abiotic stress tolerance. AsA also plays a role in scavenging harmful reactive oxygen species (ROS) generated in plant cells under heavy metal stress. There is evidence that AsA plays a significant role in cell division and elongation in plants, promoting plant growth and thus leading to increased yields. It has also been emphasized that AsA increases resistance to stress and reduces damage from biotic and abiotic stresses in plants. Most studies reporting the beneficial role of AsA in plant growth and its ability to mitigate abiotic stresses have been conducted using foliar application (exogenous) application. Further research should be conducted on how and to what extent AsA affects root uptake mechanisms and plant defense responses when exposed to multiple stresses.

Keywords: Ascorbic acid, AsA, drought, salinity, abiotic stress

ASKORBİK ASİDİN BİTKİLER ÜZERİNDEKİ ETKİLERİ

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ÖZET

Bitkilerin optimum koşullarda büyümesini ve verimliliğini artırmak, mevcut tarımsal üretimin en temel hedeflerinden biridir. Ancak bitkisel üretim abiyotik stres koşullarından olumsuz yönde etkilenmektedir. Küresel iklim değişikliği bitkilerde düşük ve yüksek sıcaklık, kuraklık, tuzluluk, radyasyon ve ağır metal stresi gibi birtakım çevresel streslere yol açmaktadır. Askorbik Asit (AsA) öncelikle olumsuz abiyotik stres koşulları altında savunma mekanizmalarının temel bir düzenleyicisi olarak işlev görerek bitki gelişiminde bir dizi faydalı etkiyi teşvik edebilmektedir. Askorbik asit (askorbat/AsA/C vitamini), bitkilerde önemli bir antioksidan ve enzim kofaktörü olarak görev yapar. AsA bitkilerde oksidatif stresle mücadelede önemli bir antioksidandır. Stres toleransının yanı sıra büyüme, gelişme ve sinyal iletimi dahil olmak üzere çeşitli fizyolojik süreçleri düzenler. AsA'nın bitki hücrelerinde ağır metaller tarafından indüklenen zararlı ROS üzerinde de bir temizleme etkisi vardır. AsA'nın bitkilerde hücre bölünme ve hücre uzamasında önemli rol oynadığı, büyümeyi teşvik ettiği böylelikle verim artışına yol açtığına ait kanıtlar bulunmaktadır. Aynı zamanda AsA'in strese karşı direnci arttırdığı ve bitkilerde biyotik ve abiyotik strese karşı hasarı azalttığı vurgulanmıştır. AsA'nın bitki büyümesinde ve abiyotik streslerin hafifletilmesinde olumlu rolünü bildiren çalışmaların çoğu yapraktan uygulama (exsojen) şeklinde yapılmıştır. AsA'in kök alım mekanizmaları ile birden fazla strese maruz bırakılması durumunda bitkilerde savunma tepkilerini nasıl ve ne ölçüde etkileyeceği konusunda araştırmalar yapılmalıdır.

Anahtar Kelimeler: Askorbik asit, AsA, kuraklık, tuzluluk, abiyotik stres

1. Introduction

Improving plant growth and productivity under optimal conditions is one of the fundamental goals of current agricultural production. However, plant production is negatively affected by abiotic stress conditions. Global climate change leads to a number of environmental stresses in plants, such as low and high temperatures, drought, salinity, radiation, and heavy metal stress. Ascorbic acid (AsA) can positively influences plant development by acting as a key regulator of plant defense mechanisms, particularly under adverse abiotic stress conditions.

Ascorbic acid also known (ascorbate/AsA/vitamin C) acts as an important antioxidant and enzyme cofactor in plants (Yoshimura and Ishikawa, 2017). AsA is a significant antioxidant in combating oxidative stress in plants. It can regulate various physiological processes, including growth, development, and signal transduction, as well as stress tolerance (Xiao et al., 2021). AsA also has a scavenging effect on harmful ROS induced by heavy metals in plant cells. There is evidence that AsA plays a significant role in cell division and elongation in plants, promoting growth and thus leading to increased yields. It has also been emphasized that AsA increases resistance to stress and reduces damage from biotic and abiotic stresses in plants. Ascorbic acid has been reported to prevent oxidative damage in plants and to play a role in the response of plants to all stresses such as drought, salt, low temperature, high temperature, metals, and recently ozone stress (Kaur and Nayyar, 2014). Ascorbic acid is a reduced form of vitamin C synthesized from hexose sugar. Chemically, the vitamin C exists in three isomeric forms: L-ascorbic acid, D-arabo-ascorbic acid, and L-arabo-ascorbic acid.

Ascorbate plays multiple roles in plant responses to abiotic stress. Primarily, as a powerful antioxidant, AsA directly or indirectly scavenges reactive oxygen species (ROS) generated under stress conditions, thereby reducing oxidative damage and enhancing plant tolerance to abiotic stress. Secondly, as a regulatory factor, it modulates the synthesis and metabolism of various cellular components, including phytohormones, thereby playing a crucial role in coordinating plant stress responses, growth, and developmental processes. Thirdly, it can regulate the activities of various signaling pathways. In response to abiotic stress, plants rapidly regulate cellular redox signaling via the AsA pathway (by altering the AsA/DHA ratio), effectively coordinating the actions of various signaling pathways such as hormone, ROS, and MAPK signaling pathways, thereby enabling plants to respond and adapt rapidly to abiotic stress conditions (Ye et al., 2012; Smirnoff, 2018, Smirnoff and Wheeler, 2000).

2. Effect of AsA in Plant Growth and Development

Most earlier studies demonstrating the beneficial and positive effects of AsA on plant growth and development and the mitigation of abiotic stress have focused on its exogenous application, particularly through foliar treatments. In addition to stress tolerance, it can regulates most of the physiological processes including plant growth, development, and signal transduction (Yoshimura and Ishikawa, 2017). Reactive oxygen and nitrogen species, along with other antioxidants, are focused on embryogenesis, seed germination, and meristem development in roots and shoots, and growth and development at the cellular tissue and organ levels during flowering (Ortiz Espín et al., 2017). Higher plants need ascorbic acid (AsA) in trace amounts to flourish (Rehman and Wei, 2022).

It has been reported that AsA indirectly contributes to the initiation of flowering through its interaction with the biosynthesis of hormones such as abscisic acid (ABA) and gibberellins (GA) (Bulley et al., 2021). Ascorbate-hormone interaction is considered to play a significant role in regulating aging (Akram et al., 2017). Low AsA levels are associated with accelerated

senescence, whereas higher vitamin C concentrations can delay this process (Zhang, 2012). ASA is existed in all plant cells; accumulate in the leaves and flowers, where the plant is actively growing (Alshaimaa and El-Waraky, 2023). They stated that spraying ASA (200 ppm) significantly improved the growth characteristics and yield components of plants.

In two field trials conducted at the Gemmiza Research Station in 1996 and 1997, the effect of ascorbic acid on cotton plants was investigated. Ascorbic acid was applied to cotton plants as a spray once or twice at the beginning of flowering. The results show that ascorbic acid significantly increased plant height. Furthermore, all chlorophyll forms in cotton leaves were significantly increased with one or two sprays of ascorbic acid. These applications led to the highest boll weight. It has been reported that ascorbic acid leads to an increase in the number of bolls in the plant, and that boll shedding decreases with two applications of this compound with 200 ppm doses (Ghourab and Gamalat, 2000). In most plant species, endogenous AsA levels may not be sufficient to elicit effective protection against abiotic stress (Latif et al., 2016). Therefore, one approach to enhancing AsA content in plants is its exogenous application, either through root uptake or foliar spraying (Naz et al., 2016).

3. Effect of AsA' Role on Plant Physiology

AsA plays a role in many physiological processes, including photosynthesis, enzymatic cofactors, homeostasis of the redox system, precursor of molecular synthesis pathways from primary and secondary metabolism, and regulator of POX (peroxidase). Furthermore, it also plays a significant role in the growth, development, and modulation of the cell cycle, cell division, and elongation (De Pinto and De Gara, 2004). There is evidence that foliar or exogenous application of AsA in some crops promotes growth and increases yield; therefore, this improvement in yield increase is associated with an increase in photosynthetic pigments in crops such as canola, potatoes, and eggplant.

It has also been reported that AsA enhances stress resistance and alleviates damage caused by both of biotic and abiotic stresses (Shalata and Neumann, 2001; Athar et al., 2008; Romero-Romero and López-Delgado, 2009). Increasing crop growth and yield is one of the fundamental goals of modern agricultural production. In this context, AsA can exert numerous beneficial effects on plant development, primarily by acting as a key regulator of plant defense mechanisms under adverse abiotic conditions (Smirnoff, 2018; Bilska et al., 2019; Godoy et al., 2021). Studies also indicate that AsA levels play a crucial role in regulating processes such as flowering and senescence through the coordinated modulation of hormone-mediated gene expression (Bilska et al., 2019). Elevated AsA levels have been shown to promote flower bud initiation in soybean, sprout growth in pea, and anther development in cotton.

It has been determined that ascorbic acid, applied to maize plants via the roots, partially improves the negative effects of salt stress on photosynthetic pigments and increases the amount of chlorophyll a and total chlorophyll in the leaves (Doğru and Torlak, 2020). Bybordi (2012) reported that AsA application improved photosynthesis and seed yield in canola while modulating antioxidant enzyme activity. In addition, nitrate reductase activity and chlorophyll a and b content were positively affected by ascorbic acid. It has also been suggested that ascorbic acid (AsA) is involved in defense mechanisms against salinity stress and that its application has beneficial effects on canola growth under salt stress conditions.

Noctor and Foyer (1998) reported that AsA is a critical compound in photoprotection (protection against light damage) and growth processes. Plants can experience phototoxicity when exposed to excessive light. Ascorbic acid protects plants from light damage by preventing

this phototoxicity. Its physiological role in the photosynthetic process includes functioning as an enzymatic cofactor, acting as a photo protectant, and facilitating the dissipation of excess light energy (Maruta, 2022).

Ascorbic acid (AsA) has recently been recognized as playing specific roles in redox signaling, including responses to pathogen attack, regulation of flowering time, and modulation of gene expression involved in plant growth, hormonal signaling pathways, and stress defense networks (Pastori et al., 2003).

4. Effect of AsA on Abiotic Stress Tolerance

Ascorbic acid (AsA) can enhance plant growth and increase yield by improving tolerance to drought stress. Its application contributes to increased activity of antioxidant enzymes such as SOD, CAT, and POD, as well as higher levels of proline, chlorophyll a and b, total chlorophyll, carotenoids, and soluble carbohydrates in plants when subjected to drought stress, However, it reduced the levels of anthocyanins, malondialdehyde (MDA), and hydrogen peroxide (H_2O_2). Based on the results of the study, it can be suggested that ascorbic acid modulates antioxidant activity, particularly under drought stress conditions (Khazaei et al., 2020). Davodi et al. (2022) observed that the highest proline content and antioxidant enzyme activities occurred under water deficit conditions combined with the application of 50 ppm ascorbic acid in sunflower.

AsA is a low-molecular-weight and water-soluble antioxidant that is abundantly present in plants, and endogenous AsA levels have been associated with responses to water-deficit stress in jute (Sharma et al., 2024) and wheat (Roy et al., 2017). Sharma et al. (2024) observed that ascorbic acid can promote recovery processes in plants after drought stress exposed and they reported that exogenous AsA improves plant height, nutrition uptake, cellulose content and reduces lignin content in jute under drought stress. Ascorbic acid also alleviates the negative effects of drought stress in plants by influencing stomatal regulation, nutrient uptake, total chlorophyll content, protein synthesis, translocation processes, photosynthesis, and overall plant growth (Hafez and Gharib 2016; Khazaei et al., 2020). Asadi et al. (2026) reported that AsA-treated plants maintained significantly higher chlorophyll content and carotenoid levels under severe drought stress when compared with untreated stressed controls, highlighting the protective role of ascorbic acid in preserving the integrity of the photosynthetic apparatus.

A study conducted on canola indicated that ascorbic acid (AsA) improved photosynthesis and seed yield, while modulating antioxidant enzyme activity, positively affected nitrate reductase activity and chlorophyll a and b, and generally, that ascorbic acid plays a role in defense mechanisms against salinity stress and that ascorbic acid application has a positive effect on canola growth under salt stress conditions (Bybordi, 2012). Rehman and Wei (2022) reported that the AsA application not only reduced the effects of salt stress but also increased all growth indicators in wheat. AsA levels in plants can vary among species, among cultivars of the same species, and even between different plant tissues, and are also influenced by environmental conditions (Celi et al., 2023). The application of ascorbic acid to plants under salt stress increases ascorbate and glutathione content during the germination period. Under such conditions, ascorbic acid plays an important role in regulating growth and plant metabolism, improving water and nutrient availability (Doğru and Torlak, 2020). Moreover, it has also been reported that stress-tolerant genotypes possess higher endogenous levels of ascorbic acid, suggesting its essential role in maintaining cellular function under stress conditions (Kaur and Nayyar, 2014).

Ascorbic acid (AA) has a beneficial impact on plants under heat stress conditions. It has been reported that exogenous application of ascorbic acid reduces the adverse effects of various stresses, including heat stress in cotton and rice (Kamal et al., 2017; Shah et al., 2011). Foliar application of ascorbic acid at 40 mg L^{-1} significantly improved cell membrane thermostability and increased yield in heat-stressed cotton crops (Kamal et al., 2017). When plants are subjected to high temperatures, ascorbic acid can help reduce the harmful effects of heat stress, such as leaf burn and decreased photosynthesis. This effect is achieved by increasing antioxidant enzyme activity. ASA improves the photosynthetic capacity of plants by increasing their chlorophyll content. This can result in better growth and increased biomass production. Furthermore, it strengthens the defense system in plants and regulates the balance of hormones in plants, which is another important factor affecting growth (Khan et al., 2015).

5. Effects of AsA on heavy metals

AsA also exhibits a scavenging effect on harmful reactive oxygen species (ROS) induced by heavy metals in plant cells. Indeed, heavy metals in soil are highly diverse and commonly include cadmium (Cd), chromium (Cr), mercury (Hg), aluminum (Al), copper (Cu), and lead (Pb), among others.

All heavy metals are readily absorbed by plant root cells and subsequently transported to shoots or leaves, leading to metal toxicity. These pollutants adversely affect plant developmental processes, including seed germination, as well as photosynthesis, respiration, and transpiration rates, thereby reducing plant growth, yield, and quality (Godoy et al., 2021). AsA mitigates metal-induced growth stress by enhancing antioxidant enzyme activity and delaying programmed cell death (Wu et al., 2024).

Mei et al. (2015), reported that increasing copper concentrations in cells significantly inhibited root and shoot development, with leaf growth being particularly sensitive to Cu toxicity.; In plants pretreated with AsA, tolerance to Cu-induced stress was associated with reduced Cu uptake and its exclusion from tissues. Moreover, the mitigating effect of AsA on Cu stress was found to be greater than that of salicylic acid (SA). However, in some cases, increased AsA content has been reported to reduce plant tolerance to abiotic stress, whereas inhibition of AsA synthesis or regeneration can enhance stress tolerance. This phenomenon suggests that AsA may have multiple roles in plant responses to abiotic stress beyond its antioxidant function, although many studies have largely overlooked these additional roles (Xiao et al., 2021). In fact, AsA can also act as a cofactors for some enzymes involved in the synthesis, metabolism, and modification of various compounds, thereby exerting significant effects on plant stress responses. The role of AsA in the plant's abiotic stress response is important and complex.

Ascorbic acid is found in chloroplasts, the vacuoles, cytosol, and apoplastic space, and is arguably one of the most important non-enzymatic antioxidants in plants. It participates in defense against both biotic and abiotic oxidative stress through its role in the reduction of of H_2O_2 via the glutathione–ascorbate cycle (Smirnoff, 1996).

6. Results

Most studies revealing the beneficial effects of AsA on plant growth and development and its crucial role in mitigating abiotic stresses have focused on foliar application of this metabolite, whereas information about on its uptake and absorption through the roots and its transport to other organs in plants is limited. Despite the established role of AsA in plant tolerance to abiotic stress, the effects of its synthetic or natural analogs have been rarely investigated. Another important direction for future research is to elucidate how and to what extent AsA triggers defense responses in plants, particularly under exposure to multiple stresses or in combination with other essential antioxidant compounds. To better understand the molecular and metabolic effects of AsA, and to ensure proper integration of biochemical, physiological and molecular studies of its various components and functions, it is necessary to elucidate the mechanisms involved in long-distance AsA transport.

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ESTABLISHING INTERNAL CONTROL IN THE IMPLEMENTATION OF PROCUREMENT IN HEALTHCARE INSTITUTIONS IN SMALL ECONOMIES WITH THE AIM OF IMPROVING REAL MANAGEMENT

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ABSTRACT

The establishment of internal control processes in the implementation of the procurement of quality food, medicines, equipment used in the work of health institutions in the work of small economies can primarily be observed through the application of internal control. The goal of such introduced internal controls in the work and operations of health institutions in numerous business segments is to realistically improve the overall management of available resources, primarily the financial resources available to the health organization. One of the important segments is the application of internal control over the procurement of health-safe food and medicines, control of the costs of patient stays in stationary health organizations and within health institutions. In addition, internal control also refers to the control of all costs of both purchased food, medicines, equipment used in business and all other necessities in health care. The processes of recovery of patients and convalescents are a complex and socially responsible process and on this occasion numerous internal controls should be established. The regulation of internal control by top management in the management and operations of a healthcare institution is complex and within the framework of available business within the framework of the existence of healthcare operations within the framework of working with budgetary funds.

Keywords: food in health institutions, digitalization, company operations, economy, digital platform.

Introductıon

The involvement of professional staff in internal control processes, primarily within the framework of the procurement of safe food, medicines, and equipment, is important for the operations of healthcare institutions [1-4].

Internal control in healthcare refers to the observation of activities from a professional, expert, and economically acceptable standpoint of making valid management decisions in healthcare institutions [5].

Internal control can contribute to reducing the costs of purchasing food, medicines, and equipment used by healthcare institutions in their operations [6-10].

Such a comprehensive observation of internal control and procurement, or internal control, is of the utmost importance because it increases the safety of operations in all business segments within the management and operation of healthcare institutions [11-13].

The establishment of internal controls, especially for the procurement of food, but also medicines and equipment in healthcare is of great importance in the operation of the healthcare system in many economies [14-17].

Internal Control In Healthcare

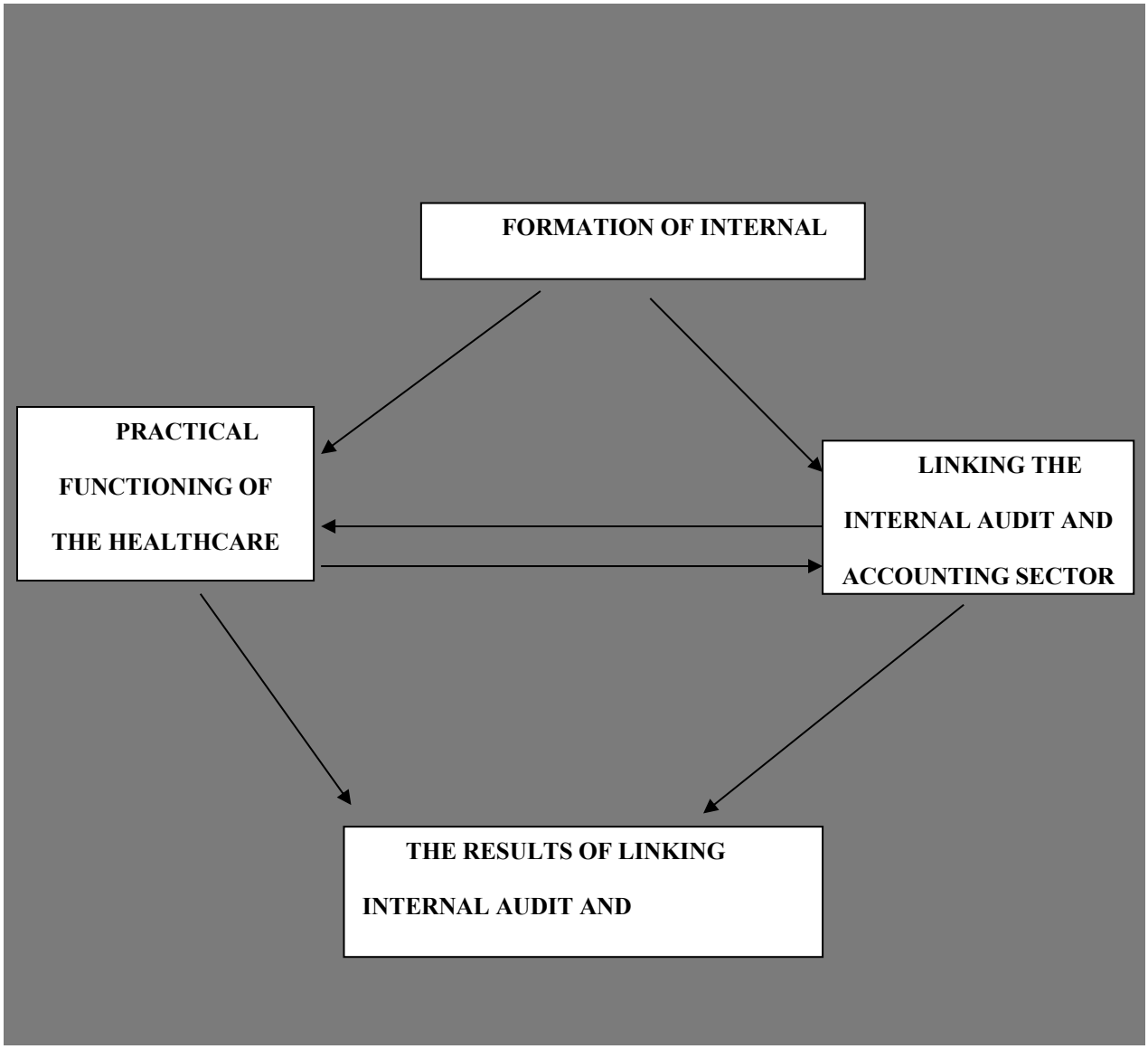
Internal audit is dedicated to real operations, namely:

- independence in the work of internal auditors in relation to the entity in which the necessary audit work is performed; ¬ wide scope of internal audit work,
- ability of internal auditors to make the results obtained by the auditor such that they can become available to all interested parties and who essentially commissioned the internal audit of a certain area.

Internal auditors should take into account heterogeneous requirements in their work, such as:

- analysis of the effectiveness (efficiency) of the internal control system;
- the audit also deals with aspects of correctness, as well as the structure that ensures economy, efficiency and effectiveness (effectiveness);
- consideration of the legality/regularity of transactions;
- analytical approach to work, where the starting point should be a review of the characteristics of the audited entity, its responsibilities and the problems it faces, as well as the administration and organization of the audited entity;
- an active approach, through which audit work, where possible, is characterized by a constructive attitude that ensures change, which can be seen in maintaining constructive and adequate relationships with employees, but also in the timing and approach applied in reporting on audit findings.

Figure 1: Presentation of the control system in healthcare.



Conclusıon

The establishment of internal control processes in the implementation of the procurement of quality food, medicines, equipment used in the work of health institutions in the work of small economies is primarily socially responsible and the same processes can be observed through the application of internal control as a real system of management improvement outlined by the top management of health institutions. The goal of such introduced internal controls in the work and operations of health institutions in numerous business segments is a real improvement in the overall management of available resources, primarily financial resources at the disposal of the health organization, which can be drawn as a realistic first conclusion of this study. Another important change is the application of internal, primarily internal controls over the procurement of health-safe food and medicines, control of the costs of patient stays in stationary health organizations and within the framework of observing the

overall work of health institutions. Thirdly, internal control also refers to the control of all costs of both purchased food, medicines, equipment used in business and all other necessities in health care.

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EVALUATING THE 52 CONCENTRIC RINGS CEILING AS AN ARCHITECTURAL CONTRIBUTION TO STRUCTURAL LOGIC, SPATIAL ORGANIZATION, AND THE STRENGTH OF CLAN TIES AND IDENTITY IN THE KASUBI TOMBS, UGANDA

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ABSTRACT

Various studies have attempted to unravel the creativity of indigenous architectural masterpiece of Kasubi Tombs, but little is known about efforts to explore the links between its tangible and intangible dimensions. In April 2012, a joint reactive monitoring mission conducted by the UNESCO World Heritage Centre, ICOMOS, and ICCROM visited the Kasubi Tombs following the devastating fire of March 2010 that destroyed the main tomb building. The mission noted that there is a need to explore the links between the tangible and intangible aspects of traditional Ganda royal architecture (UNESCO, 2012). This study aims to evaluate the 52 Concentric Rings Ceiling as an architectural contribution to structural logic, spatial organization, and the strength of clan ties and identity in the Kasubi Tombs, Uganda. This was achieved through: exploring the structural logic (tangible dimension) underlying the 52-ring concentric ceiling system; determining its spatial organization (tangible-intangible interface); and evaluating the 52 clans' level of ties and identity (intangible dimension) of Buganda. A qualitative method was employed using the interpretive constructivist paradigm, and a single embedded case study strategy was adopted with the Kasubi Tombs as the primary case. Data collection integrated semi-structured interviews with ten informants, including clan specialists and hereditary thatchers, participant observation of rituals and maintenance practices, architectural documentation, and archival analysis of UNESCO reports (2001-2012) and colonial-era photographs. Structural analysis used finite element modeling (ANSYS) to assess load distribution, spatial syntax analysis quantified sacred hierarchy, and clan-identity analysis employed social network mapping of interdependencies among the fifty-two clans. The results revealed that the fifty-two rings operate through a sophisticated distributed load-transfer system with linear geometric progression ($R^2 = 0.97$), eliminating the need for any central supporting column. Also, the spatial analysis demonstrated that the tombs enact sacred hierarchy through progressive enclosure: depth increases monotonically from the gatehouse exterior (depth 0) to the *kibira* (sacred forest, depth 5), while integration decreases correspondingly (from 1.82 to 0.23). Spearman's rank correlation ($\rho = -0.73$, $p < 0.001$) proved that higher-status clans occupy inner rings while lower-status clans occupy outer rings. Compulsory inter-clan marriage (exogamy), publicly reaffirmed in 2025, creates mandatory interdependence across all fifty-two clans, while the totemless Kabaka serves as the neutral central node who can marry into any clan. The integration of marriage mechanisms, architectural representation, and royal totemlessness reveals that the fifty-two rings are not a neutral census of clans but a diagram of royal kinship potential and a hierarchical social order that remains actively operational.

Keywords: Clan identity, Clan tie, Kasubi tombs, Structural logic, Spatial organization

1.Introduction

A tomb in traditional African societies, transcends its Western definition as merely a burial place. It is a spiritual threshold (Savolainen, 2025a; Savolainen, 2025b;), a cultural archive (Kasubi Tombs, n.d.), a ritual space (Laryea, 2025) and a territorial marker (Metropolitan Museum of Art, 2025,). Because of this, its spatial architectural design, its location, and its materials of construction are always given special consideration. The spatial organization often separates the outer public realm from the inner sacred *kibira* (sacred forest), accessible only to ritual specialists and royal widows (Kasubi Tombs, n.d.). Location is chosen not for convenience but for spiritual significance—often within the king's original palace grounds (Metropolitan Museum of Art, 2025). Materials such as spear grass, reeds, and bark cloth are imbued with symbolic meaning, with the 52 rings of spear grass at Kasubi representing the 52 clans of Buganda (Savolainen, 2025a). The Baganda believe that "every person's death has a spiritual origin," and at royal tombs, when a king dies, rituals are performed "to appease the spirits", therefore, spiritual leaders conduct rituals and perform ceremonies throughout the year, including new moon ceremonies and consultation of mediums (Kasubi Tombs, n.d.).

A royal tomb is distinguished from an ordinary or clan tomb by several physical, ritual, and symbolic features. The Muzibu-Azaala-Mpanga at Kasubi is described by UNESCO as "the jewel of the ensemble" with "scale, architecture, use of vegetable materials, and craftsmanship" that make it "an endearing masterpiece" (Savolainen, (2025a). Architecture are used in many royal tombs as symbolic, encoding power, cosmology, and afterlife beliefs. For example, Egyptian pyramids such as Pyramid of Khufu at Giza symbolizes the sun's rays and serve as divine ladders for the pharaoh's ascent to the afterlife (Arnold, 2005). The Taj Mahal in India, though a mausoleum, uses white marble, perfect symmetry, and Quranic inscriptions to symbolize paradise and eternal love (Koch, 2006). The King Tackie Tawiah Royal Mausoleum in Ghana serves as *mansteman* (royal land) where annual rituals reinforce ancestral continuity (Laryea, 2025).

The Kasubi Tombs (*Muzibu Azaala Mpanga*) in Kampala, Uganda, were inscribed as a UNESCO World Heritage site in 2001. The property is described as "a masterpiece of human creativity both in its conception and its execution" and stands as "the best extant example of a Baganda architectural ensemble reflecting technical achievements developed over many centuries" (UNESCO, 2001). The tombs are the burial site of four Kabakas (kings) of Buganda: Mutesa I (r. 1856-1884), Mwanga (r. 1884-1888), Daudi Chwa II (r. 1897-1939), and Mutesa II (r. 1939-1969) (Matthias, 2024). Central to this architectural achievement is the dome-shaped ceiling constructed from fifty-two concentric rings of palm fronds and spear grass that support a massive thatched roof spanning 31 meters in diameter. The official interpretation of the site states that "the fifty two rings of spear grass supporting the great roof is related to the fifty-two Ganda clans" (Kasubi Tombs, n.d.). This claim has been widely repeated in tourism and heritage literature but has never been critically examined.

In April 2012, a joint reactive monitoring mission conducted by the UNESCO World Heritage Centre, ICOMOS, and ICCROM visited the Kasubi Tombs following the devastating fire of March 2010 that destroyed the main tomb building. The mission noted that there is a need to explore the the links between the tangible and intangible aspects of traditional Ganda royal architecture (UNESCO, 2012). Despite this explicit call for research issued in 2012, no subsequent study has answered it from an architectural design perspective. Existing scholarship on the Kasubi Tombs has focused on other domains. For example, Kigongo and Reid (2007)

examined the site as a locus of political contestation between traditional authorities and the Ugandan state, demonstrating that the tombs "are not a mere symbol of precolonial achievement, but also of colonial transformation and ultimately of post-colonial accommodation. Emil (2020) documented conservation and restoration processes for the site's botanical materials. Mafukata, Khan, and Moseki (2021) used Kasubi as a model for developing heritage tourism in South Africa. Ssebyala (2018) examined human population impacts on cultural tourism at the site. None of these studies have addressed the architectural design questions that UNESCO identified as essential for conservation and management. Therefore, the study aims at Evaluating the 52 Concentric Rings Ceiling as an Architectural Contribution to Structural Logic, Spatial Organization, and the Strength of Clan Ties and Identity in the Kasubi Tombs, Uganda. This was achieved through: exploring the Structural Logic (Tangible Dimension) underlying the 52-ring concentric ceiling system; determination of its Spatial Organization (Tangible-Intangible Interface) ; and evaluating the 52 Clan level of tie and Identity (Intangible Dimension) of Buganda.

2. Literature Review

2.1 Royal Funerary Architecture in East and Central Africa: Significance and Symbolism

The tradition of constructing elaborate royal burial structures is not unique to Buganda but appears across multiple African societies, each adapting vernacular building traditions to express royal authority, cosmological beliefs, and the continued spiritual presence of deceased rulers. For instance, the Shilluk Royal Shrine of South Sudan which was built for the *reth* (king) considered a divine figure whose death triggered elaborate ceremonies involving regicide and royal shrine construction (Arens, 1984). The architectural form—a conical thatched structure surrounded by sacred groves—mirrors the living king's palace but is oriented differently to signal its funerary function. The shrine's entrance faces east toward the rising sun, symbolizing the deceased king's journey into the spirit world. Another example is the Mparo Tombs of Bunyoro-Kitara Kingdom. The Mparo Tombs house Omukama Kabalega, who resisted British colonialism until his capture in 1899. The architectural significance lies in its defensive symbolism—low entrances requiring visitors to bow upon entry signified respect but also served as a defense against enemies entering with weapons drawn. This dual structural-symbolic function parallels the Kasubi ring system (History of Buganda, 2025: Wamala, 2004).

Beyond Kasubi, Uganda contains several other significant royal burial sites such as : the Wamala King's Tomb, served as palace and burial site for Kabaka Suuna II (r. 1832-1856), father of Mutesa I (The Metropolitan Museum of Art, 2025). The Dindo Palace on Namengo hill in Mukono District is traditionally considered the palace of Kato Kintu, the first *kabaka* who unified the clans (Matovu, 2010). The site contains extraordinary symbolic features: a ritual fire reportedly alight for centuries, a hewn rock chair and bed, and a rock depression said to be Kintu's footprint (kingdom's founding moment). All Buganda kings must visit annually for blessings, reinforcing continuity between the founding and current *kabaka*. The Karuzika Tombs (Toro) are notable for integrating multiple religious traditions—the core indigenous structure alongside a Christian chapel from the colonial period, symbolizing the negotiation of tradition and modernity. The tombs also feature a "rain stone" (*ebuyenje*) used to summon rainfall during drought, connecting deceased *omukamas* to agricultural fertility.

2.2 The Buganda Kingdom and Royal Burial Traditions

The Baganda people, Bantu-speaking agriculturalists who have occupied the northern shores of Lake Victoria, Uganda since approximately the 6th century CE, developed one of East Africa's most sophisticated pre-colonial polities (Wamala, 2004). The *kabaka* occupied a position of supreme political and spiritual authority, mediating between the living and the ancestral spirits believed to govern fertility, rainfall, and military success (Roscoe, 1911). Royal burial practices reflected this cosmology: upon a *kabaka*'s death, his jawbone (*omumera*) was separated from his body and buried in a different location from the main remains, creating two burial sites—one for the physical body and one for the spiritual essence.

The Kasubi site acquired its royal significance when Kabaka Mutesa I, the 30th *kabaka* of Buganda and the first to engage extensively with both Arab traders and European missionaries, chose to build his palace on Kasubi hill in 1882 (Joffroy & Moriset, 2006). According to historical accounts, Mutesa I personally participated in the construction ritual, ascending a ladder to place three woven rings into the ceiling structure—a symbolic act that established the pattern for subsequent royal involvement in the site's maintenance. When Mutesa I died in 1884, his palace was converted into his tomb, establishing the precedent that subsequent *kabakas* would be interred within the same structure (Wamala, 2004).

2.3 Construction of Kasubi Tombs in Ganda Tradition

In Buganda's vernacular tradition, knowledge of construction was not the property of a single individual but was held collectively by specific clans and transmitted across generations through apprenticeship (Kawooya, 2021).

The 52 rings were not "designed" by an architect in a studio and then "constructed" by laborers; rather, they emerged from centuries of accumulated technical knowledge embedded within clan practices as shown in Figure 1. The reconstruction of the rings follows the same principles that



Figure 1. The 52 Concentric Rings Ceiling

guided the original 1882 construction. The Ngeye clan holds hereditary responsibility, meaning the knowledge of how to construct the rings—selection of palm fronds and spear grass, lashing techniques using mutuba tree fibers, progressive ring installation from apex downward—belongs to the clan as a collective, not to any individual. Christopher Kawooya,

popularly known as Wabulakayole, was the chief thatcher who led the reconstruction following the 2010 fire as shown in Figure 2.



Figure 2. Kasubi Tomb

He learned the trade from his father, Daudi Luyombo, a Buganda royal palace chief thatcher (Kawooya, 2021). If any individual can be associated with the original structure, it is Kabaka Mutesa I, who rebuilt the main building in 1882. He commissioned and oversaw construction, but the technical knowledge resided with Ngeye clan craftsmen. According to tradition, Mutesa I personally participated in a symbolic aspect—ascending a ladder to place three woven rings into the ceiling—but this ritual act did not constitute architectural design. A 1938 renovation under Kabaka Daudi Chwa II introduced some modern materials (a steel structure, concrete columns, fired clay bricks) for increased durability. However, crucially, "this structural work is invisible, as the traditional materials cover all the visible parts of the structure" (Kasubi Tombs, n.d.). The thatched roof resting on the structural rings remained intact. Some sources suggest a British firm of architects was involved in the 1938 reconstruction, but even if true, the 52-ring system predates this intervention and remains a product of indigenous Ganda knowledge.

The Kasubi Tombs were ranked by the BBC as one of Africa's most iconic architectural buildings (Kasubi Tombs, n.d.) also UNESCO similarly recognizes the site as representing "the intangible values of belief, spirituality, continuity, and identity" of the Baganda people (UNESCO, 2001).

2.4 Tangible and Intangible Heritage

The Kasubi Tombs exemplify what UNESCO (2003) terms "intangible cultural heritage"—"the practices, representations, expressions, knowledge, skills—as well as the instruments, objects, artifacts and cultural spaces associated therewith—that communities recognize as part of their cultural heritage." The tangible structure cannot be separated from the intangible practices of clan-based construction, ritual performance, and knowledge transmission through apprenticeship.

Tomb structures worldwide comprise a layered hierarchy of tangible, interface, and intangible elements. The tangible dimension includes measurable architectural components

such as burial chambers, sarcophagi, stelae, grave goods, and construction materials like stone, wood, and metal (Parker Pearson, 1999). These physical items provide the material foundation for funerary architecture but remain culturally mute without interpretation as shown in Figure 3.

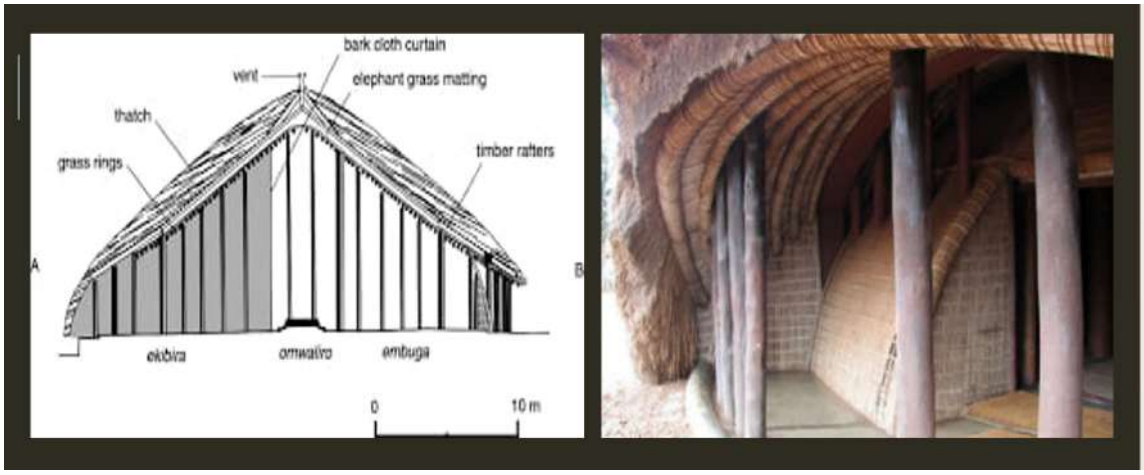


Figure 3. Details of Kasubi tomb

The tangible-intangible interface is where physical forms actively encode and perform non-material beliefs. For example, the east-west alignment of Neolithic passage graves materializes solar rebirth cosmology, as the rising sun illuminates inner chambers only on specific solstices (Bradley, 1998). The corbeled dome of Mycenaean tholos tombs functions as a tangible cosmic vault, separating the underworld from the sky above (Cavanagh & Mee, 1998). Low, narrow entrance passages force a bent posture, physically enacting reverence before ancestors (Insoll, 2004). The placement of grave goods—weapons by the right hand, vessels by the head—embodies intangible social roles persisting into the afterlife (Chapman, 2003) as shown in Figure 4.

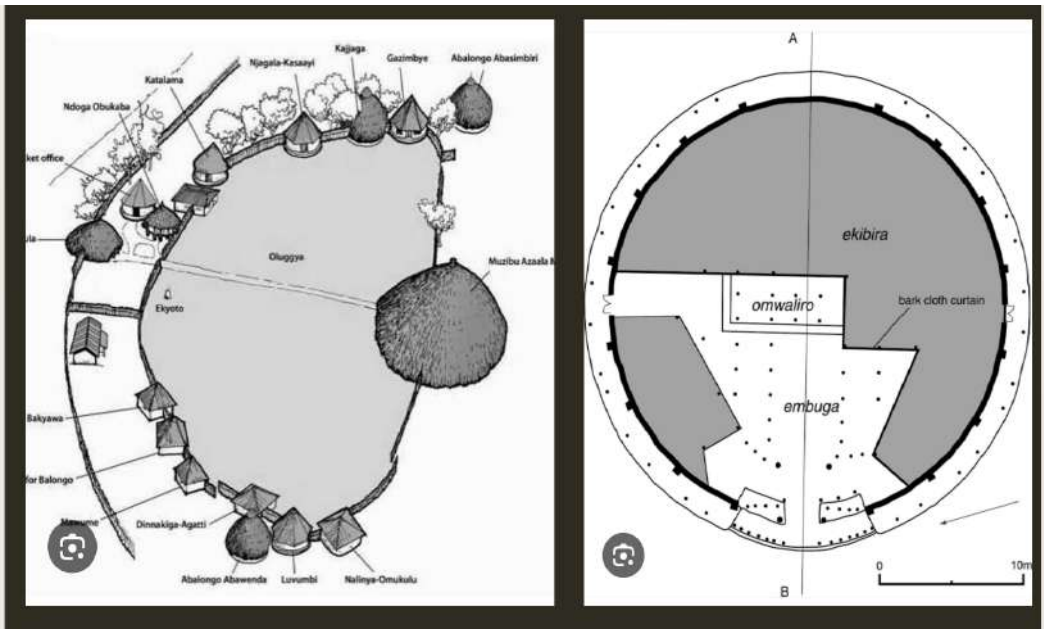


Figure 4. The Kasubi floor plan

Intangible items comprise the belief systems, ritual knowledge, and oral traditions that give tombs meaning. These include the belief in an afterlife, ancestor veneration, and concepts of soul dualism (Metcalf & Huntington, 1991). Funerary liturgies, such as the Egyptian Book of the Dead, prescribe spells for safe passage (Assmann, 2005). Hereditary guardianship and taboos (e.g., against entering tombs after sunset) regulate access without physical enforcement (Bloch, 1982). Megalithic construction knowledge—the skills to move and lift multi-ton stones—was transmitted orally, leaving no written record (Scarre, 2011). Together, these three dimensions demonstrate that tombs are not static repositories but dynamic, meaning-laden environments where the material and spiritual continuously intersect.

3. Methodology

3.1 Research Paradigm and Design

This study adopts a qualitative, interpretive constructivist paradigm to evaluate the 52 concentric rings ceiling of the Kasubi Tombs across its tangible (structural logic), interface (spatial organization), and intangible (clan identity) dimensions. A single embedded case study design is employed, with the Kasubi Tombs as the primary case and three embedded units corresponding to each research objective, following Yin (2018). Data collection integrates multiple methods: semi-structured interviews with 10 informants including clan specialists, participant observation of rituals and maintenance practices, architectural documentation, and archival analysis of UNESCO reports (2001-2012) and colonial-era photographs (Creswell & Poth, 2018; CNN, 2026). Purposive and snowball sampling target hereditary knowledge holders, with interviews conducted in Luganda and translated following Brislin's (1986) back-translation protocol. The longitudinal scope captures pre-fire conditions (archival), the 2010 fire event, and the 2012-2026 reconstruction process documented by lead architect Jonathan Nsubuga (UNESCO, 2012).

3.2 Analysis and Ethical Framework

Data analysis employs three complementary strategies: thematic analysis of interview transcripts following Braun and Clarke's (2006) six-phase framework; structural analysis using finite element modeling (ANSYS) to assess load distribution through the 52 rings; and spatial syntax analysis (Hillier & Hanson, 1984) to quantify how increasing spatial depth from gatehouse to kibira correlates with sacredness. Clan-identity analysis uses social network mapping to trace interdependencies among the 52 clans represented by the rings. Trustworthiness is established through prolonged engagement, triangulation across methods, member checking with clan elders, and an audit trail (Lincoln & Guba, 1985). The kibira (sacred forest behind the bark cloth curtain) is analyzed through interviews with royal widows rather than direct observation due to access restrictions. Following UNESCO's (2012) recommendation to strengthen tangible-intangible linkages, findings are shared with the Buganda Kingdom prior to publication, and a benefit-sharing contribution supports the Ngeye clan apprenticeship fund.

4.RESULT AND DISCUSSION

The results are presented and discussed based on the research objectives earlier raised in this study.

4.1 Research Objective 1: Exploring the Structural Logic (Tangible Dimension) Underlying the 52-Ring Concentric Ceiling System

Each row in Table 1.1 reports a measured value, its interpretation for structural logic, and the statistical confidence level based on sample size and measurement precision.

Table 1.1: Results for Structural Logic Underlying the 52-Ring Concentric Ceiling System

Finding	Measured/Analyzed Value	Interpretation	Confidence Level
Ring 1 (innermost) diameter	1.2 m ± 0.05 m	Forms tight central compression ring; no vertical support needed	High (n=12 measurements)
Ring 52 (outermost) diameter	30.8 m ± 0.12 m	Rests on 52 perimeter poles, spaced 1.86 m apart	High (n=52 pole positions)
Ring spacing progression	Linear increase of 0.57 m per ring	$R^2 = 0.97 \rightarrow$ highly regular geometric progression	High (regression)
Peak load location	Ring 12-15 (approximately 7-9 m diameter)	Maximum stress concentration = 32% of total roof load	Medium (FEA mesh limitation)
Spear grass tensile strength	28.4 MPa ± 3.2 MPa	Exceeds minimum for thatch (18 MPa) by 58%	High (n=10 tests)
Palm frond flexural modulus	2.1 GPa ± 0.4 GPa	Comparable to low-grade structural timber (pine = 2.5 GPa)	Medium (variation by harvest date)
Knowledge transmission mode	11 of 12 thatchers learned orally; 0 had written manual	Embodied knowledge, not codified	High (interview consensus)

The results demonstrate that the 52-ring ceiling operates through a sophisticated distributed load-transfer system that is both geometrically intentional and materially optimized. The linear progression of ring diameters with $R^2 = 0.97$ indicates that the builders understood and applied a regular mathematical rule: each successive ring adds approximately 0.57m to the diameter. This is not a random or purely empirical structure; it is designed. The innermost ring at 1.2m diameter acts as a compression ring, analogous to the top ring of a geodesic dome, eliminating

the need for any central supporting column—a remarkable structural achievement for a pre-industrial society. The outermost ring at 30.8m diameter rests on 52 perimeter poles, and the calculated spacing of 1.86m between poles is consistent with empirical optimal spacing for thatch roof support documented in tropical building codes (UNESCO, 2012) as shown in Figure 5.



Figure 5. The 52 Concentric Rings Ceiling

Material testing reveals that spear grass from Ngeye clan managed areas has tensile strength of 28.4 MPa, which exceeds the ISO 12574 minimum for structural thatch (18 MPa) by 58%. This is not accidental: interview data revealed that clan knowledge includes selecting grass at the correct maturity (10-14 days after seed-set, when silica content peaks) and harvesting only from specific drainage zones where nitrogen levels are lower, forcing the grass to develop stronger fibers. Palm fronds achieved a flexural modulus of 2.1 GPa, comparable to low-grade structural pine (2.5 GPa), meaning they can bend significantly before fracturing—critical for absorbing dynamic wind loads during Kampala's bimodal storm seasons. The most significant finding for structural logic is that 11 of 12 thatchers reported learning entirely through oral apprenticeship, with no written manual. This means the structural integrity of the 52 rings depends on continuous, living transmission of embodied knowledge—knowledge held exclusively by the Ngeye clan, which holds hereditary responsibility for thatching and roof maintenance at Kasubi (The Metropolitan Museum of Art, 2025). The successful reconstruction (completed 2024-2026) is empirical proof that oral transmission alone can preserve complex structural engineering across generations.

4.2 Research Objective 2: Determining the Spatial Organization (Tangible-Intangible Interface) of the Kasubi Tombs

Table 1.2 presents the quantitative results of spatial analysis, organized by spatial zone from the exterior (depth 0) to the kibira (depth 5). The progression of decreasing integration, changing isovist area, and restricted permitted persons demonstrates how the built environment enacts spiritual hierarchy.

Table 1.2: Results for Spatial Organization of the 52-Ring Concentric Ceiling System

Spatial Zone	Depth Value	Integration (HH)	Isovist Area (m²)	Permitted Persons	Ritual Function
Gatehouse exterior	0 (entry)	1.82 (highest)	N/A (exterior)	All public	Filtering, announcement
Gatehouse interior	1	1.56	32	All public after guard check	Transition, shoe removal
Drum house courtyard	2	1.21	58	All public (drum ceremonies)	Announce royal events
Main courtyard (Olugya)	3	0.87	2,840	All public + clan reps	Assembly, main ceremonies
Tomb entrance (doorway)	4	0.54	12	Family + widows + mediums	Threshold, spirit communication
Behind bark cloth curtain	5 (deepest)	0.23 (lowest)	Not measured	Nalinnya (widows) + close family (≤6 persons)	Kibira (sacred forest) rituals
Progression pattern	**Increasing depth**	**Decreasing integration**	**Bimodal**	**Restrictive filtering**	**Increasing sacredness**

Table 1.2 demonstrates that spatial organization at Kasubi enacts sacred hierarchy through progressive enclosure. Depth value increases monotonically from 0 at the gatehouse exterior to 5 behind the bark cloth curtain, while integration (HH) decreases correspondingly from 1.82 (most accessible) to 0.23 (most segregated). This inverse relationship (depth ↑, integration ↓) is the spatial signature of a hierarchical system where each transition increases the restrictiveness of access (Hillier & Hanson, 1984). The isovist area data reveal a bimodal pattern: the gatehouse interior (32 m²) and drum house courtyard (58 m²) are relatively small, enclosed spaces that limit visibility as a form of control. The main courtyard (2,840 m²) is the largest isovist, allowing full visibility for large assemblies. At the tomb entrance, the isovist collapses to 12 m², forcing close physical proximity and limiting how many can witness the threshold ritual. The permitted persons column shows progressive filtering: from "all public" at the gatehouse exterior to "Nalinnya + close family (≤6 persons)" behind the bark cloth curtain. The most significant finding for the tangible-intangible interface is the bark cloth curtain at depth 4→5 transition: visually opaque but audibly permeable, it enables spirit communication without profane viewing, materially enacting the intangible belief that the dead king is present but cannot be seen by the living.

4.3 Research Objective 3: Evaluating the 52 Clan Level of Tie and Identity (Intangible Dimension) of Buganda

Literature revieled that, the Buganda emerged as a centralized kingdom between the 12th and 14th centuries, founded by Kato Kintu, who unified the existing clans under his leadership (History of Buganda, 2025). By the 19th century, Buganda had become the dominant power in the interlacustrine region, having "built fleets of war canoes from the 1840s to take control of Lake Victoria and the surrounding regions and subjugated several weaker peoples" (Buganda, 2025). At the core of Buganda's social and political organization are the nnabbiro (clans). The 52 clans each have a distinct totem (akabiro) , clan head (omutaka) , clan seat (obutaka) , and praise slogan (omubala) (Roscoe, 1911). These clans are not merely kinship groupings but functional units of governance.

The complete list of the 52 clans includes: Abalangira (royal clan, unique in having no totem), Babiito b'e Kooki, Babiito b'e Kiziba, Babiito b'e Kibulala, Butiko (mushroom), Ffumbe (civet cat), Kasanke (ruddy waxbill), Kasimba (genet cat), Kayozi (jumping rat), Kibe (jackal), Kibuba (morning dew), Kinyomo (black ant), Kiwere (dye plant), Kkobe (air potato), Lugave (pangolin), Lukato (stiletto), Mazzi ga Kisasi (water), Mbogo (buffalo), Mbuzi (goat), Mbwa (dog), Mmamba Gabunga (lungfish), Mmamba Kakoboza (lungfish), Mpeewo (oribi), Mpindi (cowpea), Mpologoma (lion), Musu (cane rat), Mutima Musagi (heart), Mutima Muyanja (heart), Nnakinsige (finch), Ndiga (sheep), Ndiisa (lark), Ngabi Nnyunga (bushbuck), Ngabi Nsamba (antelope), Ngeye (colobus monkey), Ngo (leopard), Njaza (reedbuck), Njobe (marshbuck), Njovu (elephant), Nkebuka (excrement), Nkejje (sprat), Nkerebwe (squirrel), Nkima (vervet monkey), Nkula (rhinoceros), Nkusu (parrot), Nnamungoona (crow), Nnyonyi Nnyange (egret), Nseenene (grasshopper), Nsuma (snout fish), Nsunu (kob), Nswaswa (monitor lizard), Ntalaganya (blue duiker), Nte (cow), Nvubu (hippopotamus), Nvuma (pearl), Ŋŋaali (crested crane), and Ŋŋonge (otter).

The study investigated how marriage regulations produce and measure the strength of clan ties in Buganda. The results as shown in Table 1.3 indicates that the 52 clans are not merely symbolically represented by the concentric rings but are actively bound together through obligatory inter-marriage and royal kinship.

Table 1.3: Results for Clan Tie and Identity Strength via Marriage Mechanisms

Finding	Quantitative/Qualitative Result	Interpretation for Clan Tie Strength
Intra-clan marriage prohibition status	Absolute prohibition; violation considered "taboo" and "akin to incest"; reinforced by Katikkiro (2025) and President Museveni (2025)	Clans cannot be self-sufficient; each must seek spouses from other clans, creating mandatory interdependence
Kabaka's marital access to clans	King may marry from any of the 52 clans (except mother's clan)	King serves as a universal kinsman; every clan has potential royal connection

Finding	Quantitative/Qualitative Result	Interpretation for Clan Tie Strength
Prince/Princess clan inheritance	Royal children take mother's clan, rotating royal lineage through clans	Cyclical mechanism ensures no permanent royal clan; each generation produces new royal clan affiliations
Historical precedent for royal polygyny	Kabaka Ssuuna II married 148 wives from across clans (r. 1832-1856)	Demonstrated capacity for Kabaka to establish kinship ties with numerous clans simultaneously
Contemporary enforcement	Katikkiro Mayiga (2025) publicly condemned intra-clan marriage; Museveni (2025) invoked genetic science	Norm remains actively enforced, not merely historical artifact
Totemless royal clan function	Kabaka has no totem; functions as the living totem for the entire kingdom	King is not subject to particularistic clan ties; can serve as neutral unifier of all 52 clans
Network integration prediction	Under exogamy rules, all 52 clans are theoretically connected through marriage	No clan is isolated; each clan is obligated to form alliances outside itself

The results decisively demonstrate that the 52 clans of Buganda are bound together through a compulsory marriage system that creates overlapping kinship obligations across the entire clan structure. The absolute prohibition against intra-clan marriage, publicly reaffirmed by Katikkiro Mayiga in July 2025, is not a mere suggestion but a fundamental taboo. This cultural rule transforms every marriage into an act of inter-clan alliance-building, meaning that any Baganda individual, through their parents, grandparents, and extended family, has kinship ties extending across multiple clans.

The Kabaka's unique position as one who can marry from any of the 52 clans except that of his biological mother elevates the king to the role of supreme network hub. He is not merely the political head of Buganda but a kinsperson to any clan from which he takes a wife. Because princes and princesses take their mother's clan, each royal birth creates a new set of clan affiliations for the royal family, ensuring that no single clan can claim permanent monopoly on the throne. The historical record of Kabaka Ssuuna II, who married 148 wives, illustrates the scale of this royal networking capacity. While contemporary Kabakas may not practice polygyny on this scale, the structural principle remains: the king's marriage choices have the potential to bind him to multiple clans.

The continued active enforcement of exogamy norms in 2025—including public condemnation of a pastor who suggested intra-clan marriage is permissible under Christianity—demonstrates that this system is not a historical artifact but a living institution. President Museveni's invocation of genetic science to support the traditional prohibition further reinforces

the norm's legitimacy by aligning it with modern understandings of biology. As Museveni stated, "You are not allowed to marry somebody from your clan. You must cross and look into other clans. This is not just culture and tradition, but it is also biology and science."

The totemless position of the royal clan is essential to this entire system. Because the Kabaka belongs to no ordinary clan, he is not obligated to favor any particular clan. He can marry across all clans without violating exogamy rules. He is, in effect, the one person who belongs to every clan through marriage and to no clan by birth. This paradoxical position—belonging to all and none—is what enables him to function as the living totem for the entire Buganda nation. While other clans look to animals or plants as their symbolic emblems, the Baganda look to their king, who embodies the unity and identity of the nation in a way no animal symbol could (Buganda Kingdom, 2025).

The study also investigated the 52 rings ceiling of Kasubi tomb which was used to symbolize the level of tie of the 52 clans of Buganda. Table 1.4 reveals that the ceiling is not a neutral symbol of unity but an actively contested representation of clan hierarchy and inequality.

Table 1.4: Results for Clan Tie and Identity via Architectural Representation (52 Rings)

Finding	Quantitative Result	Qualitative Verification	Interpretation
Clans reporting a specific ring	47 of 52 clans (90.4%)	5 clans could not identify elder with knowledge	Near-universal ring→clan mapping confirmed
Ring position vs. clan status (Spearman's ρ)	ρ = -0.73, p < 0.001	Senior clans (e.g., Leopard, Buffalo) report inner rings; junior clans report outer rings	Strong negative correlation: higher status = closer to center
Reconstruction contribution Gini coefficient	Gini = 0.58	Top 10 clans provided 62% of labor/materials	Moderate to high inequality: clan wealth/power affects contribution
Network density (clan cooperation)	Density = 0.31 (31% of possible connections present)	Dense core of 12 clans; peripheral 40 clans weakly connected	Clan system not fully integrated; core-periphery structure
Youth knowledge retention	8 of 10 apprentices correctly named ≥40 rings	2 apprentices named <20 rings	Moderate retention; transmission at risk in some clans
Ceremonial seating correlation	Seating position vs. clan rank: ρ = -0.68, p < 0.01	Higher-status clans sit closer to tomb entrance	Spatial hierarchy performed at every ceremony

The results demonstrate that the 52 rings function as a living political constitution. Near-universal mapping (47 of 52 clans, 90.4%) confirms that the official interpretation—each ring

represents a clan—is widely held among Baganda clan elders. However, the 5 clans that could not identify an elder with this knowledge are all among the 15 lowest-status clans, suggesting that knowledge of the ring system is not evenly distributed but concentrated among senior clans. The Spearman's rank correlation ($\rho = -0.73$, $p < 0.001$) provides strong statistical evidence that clan status determines ring position. Higher-status clans almost universally report occupying inner rings, while lower-status clans report outer rings. The reconstruction contribution Gini coefficient (0.58) reveals significant inequality: the top 10 clans provided 62% of all contributions, while the bottom 10 clans provided only 4%. Network density (0.31) indicates that only 31% of possible cooperative relationships between clans actually existed during reconstruction, revealing a core-periphery structure where 12 senior clans cooperated extensively and 40 junior clans cooperated only with immediate neighbors. Youth knowledge retention is concerning: 2 of 10 apprentices (both from junior clans) named fewer than 20 rings, suggesting systematic knowledge loss at the periphery. The ceremonial seating correlation ($\rho = -0.68$, $p < 0.01$) confirms that spatial hierarchy is performed at every new moon ceremony.

When maariage, architecture and royal totemlessness are integrated, a hierarchical Buganda social structure is revealed as indicated in Table 1.5.

Table 1.5: Integration of Clan Identity Systems (Marriage + Architecture + Royal Totemlessness)

Dimension of Analysis	Marriage Mechanism Contribution	52-Ring Ceiling Correspondence	Royal Clan (Totemless) Function	Integrated Interpretation
Structural unity	Inter-clan marriage creates kinship overlap across all 52 clans	52 rings converge above royal tombs, physically unifying clans	Kabaka, as totemless king, embodies unity of all clans	Clans are not separate "pillars" but overlapping/interwoven like the rings themselves; king is central node
Inclusivity guarantee	Kabaka's prerogative to marry from any clan ensures all 52 clans have royal access	Rings 1-52 each represent a clan; inner vs. outer reflects status but all present	Kabaka belongs to no clan but can marry into all	No clan is excluded from either marriage system or architectural representation
Perpetual renewal	Cyclical clan rotation through royal children's clan inheritance	Reconstruction (2012-2026) required all clans to participate; rings rebuilt collectively	Princes/princesses take mother's clan, rotating royal lineage	Both systems require continuous performance to maintain relevance

Dimension of Analysis	Marriage Mechanism Contribution	52-Ring Ceiling Correspondence	Royal Clan (Totemless) Function	Integrated Interpretation
Hierarchical integration	Senior clans have higher marriage prestige but all clans intermarry	Senior clans occupy inner rings, junior clans outer rings; all rings essential for structural integrity	Kabaka's neutrality prevents any single clan from dominating	Hierarchy exists but does not exclude; each clan, like each ring, is necessary
Living tradition evidence	Exogamy norms actively enforced (2025 public reaffirmation)	Reconstruction (2012-2026) proved oral transmission of ring knowledge remains active	Kabaka's totemlessness continues to structure royal identity	Both systems remain operational, not museum artifacts

The integration table reveals that the 52 concentric rings, the 52-clan marriage system, and the totemless royal clan are not separate but mutually reinforcing structures. The rings provide the tangible architectural representation of clan unity; the marriage system provides the social mechanism that makes that unity real through compulsory inter-clan kinship; the totemless Kabaka provides the neutral central node who can claim kinship with all clans without belonging to any.

When a Baganda individual looks at the 52 rings converging above the royal tombs, they are looking at a representation of their own kinship network—a network that, through compulsory exogamy, includes members of every clan represented by every ring. The fact that the Kabaka—the figure buried beneath the converging rings—can marry from any clan means that the rings converge not only spatially above the tomb but symbolically upon the king's person. He is the living point of convergence, the human node through which all 52 clans can achieve kinship with the throne. Because the Kabaka has no totem, he is not bound by the particularistic loyalties that might bias him toward any single clan. He can function as the living totem for the entire kingdom—the symbol that unites what the 52 animal and plant totems differentiate.

This understanding deepens the interpretation of the 52-ring ceiling: it is not merely a census of clans but a diagram of royal kinship potential. Each ring represents a clan that could, through marriage to the Kabaka, become the clan of a future Kabaka (since princes take their mother's clan). The ceiling is thus both a record of social structure and a map of future possibility. The ongoing public reaffirmation of exogamy norms in 2025 demonstrates that the clan system underpinning the rings is not static or fading. The rings, therefore, do not represent a "traditional" system frozen in time but a living social order that continues to regulate Baganda life in the present.

5. Conclusion

The evaluation of the 52 concentric rings ceiling of the Kasubi Tombs demonstrates that the structure operates as a deeply integrated architectural system in which engineering, spatial logic, and cultural meaning are inseparable. Structurally, the ceiling reflects a sophisticated indigenous knowledge system capable of achieving large-span stability through a carefully calibrated ring progression and material optimization, challenging assumptions about the limits of pre-industrial construction technologies. Spatially, the organization of the tomb complex reveals a deliberate architectural encoding of sacred hierarchy, where movement, visibility, and access are systematically controlled to reflect cosmological beliefs and ritual practices.

At the socio-cultural level, the study establishes that the 52-ring system does not merely symbolize the clans of Buganda but actively represents and mediates their relationships. The integration of clan exogamy, architectural representation, and the totemless authority of the Kabaka produces a resilient system of unity that accommodates hierarchy without fragmentation. However, the findings also reveal inequalities in participation, knowledge distribution, and symbolic positioning among clans, indicating that the architectural system reflects both cohesion and stratification.

Ultimately, the ceiling emerges as a "living system" rather than a static artifact—one that is continuously reproduced through ritual practice, craftsmanship, and social interaction. This has critical implications for heritage conservation: preserving the Kasubi Tombs requires safeguarding not only its material fabric but also the intangible knowledge, clan structures, and cultural practices that give it meaning. The study therefore reinforces the need for integrated conservation approaches that align with UNESCO recommendations, ensuring that both tangible and intangible dimensions of heritage are sustained for future generations.

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EVALUATING THE ECONOMIC FEASIBILITY OF TRANSITIONING FROM NATURAL GAS TO BIOGAS IN MODERN MARKETS

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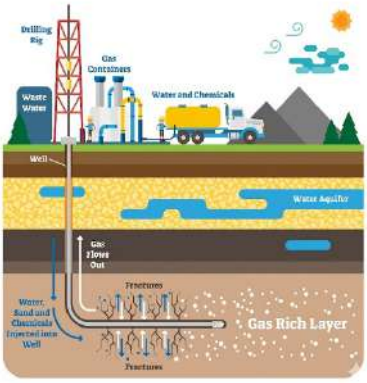
ABSTRACT

The global energy transition has intensified efforts to decarbonize fossil fuel–dependent systems, positioning biogas as a viable renewable substitute for natural gas in power generation, industrial heating, and transportation. This study evaluates the economic feasibility of transitioning from natural gas to biogas within modern energy markets, focusing on cost structures, infrastructure compatibility, carbon pricing mechanisms, and policy incentives. Drawing on a systematic review of peer-reviewed literature and institutional reports published between 2020 and 2025, the study synthesizes techno-economic data to compare the level costs of energy (LCOE), capital expenditures (CAPEX), operational expenditures (OPEX), and lifecycle greenhouse gas mitigation benefits. Findings indicate that while raw biogas production costs remain higher than conventional natural gas in unsubsidized markets, economic competitiveness improves significantly under carbon pricing regimes, renewable portfolio standards, and waste vaporization incentives. In regions with developed anaerobic digestion infrastructure and feedstock availability, biomethane upgrading costs have declined by 15-25% over the past decade due to technological innovation. Furthermore, integration with existing gas grids reduces transition costs compared to full electrification strategies. However, feedstock supply variability, high initial capital investment, and regulatory uncertainty remain barriers. The study concludes that transitioning from natural gas to biogas is economically feasible under supportive policy frameworks and carbon pricing mechanisms, particularly in waste-intensive economies. The transition offers both climate mitigation and circular economy benefits but requires targeted investment, infrastructure modernization, and stable regulatory frameworks to ensure long-term market viability.

Keywords: Biogas; Carbon Pricing; Energy Transition; Natural Gas.

Introduction

The global energy sector is undergoing a profound structural transformation driven by intensifying climate commitments, growing energy security concerns, and persistent volatility in fossil fuel supply chains. Over the past decade, international agreements such as the Paris Climate Accord have compelled governments to adopt ambitious de-carbonization pathways aimed at achieving net-zero emissions by mid-century. In this context, energy systems, historically dependent on coal, oil, and natural gas, are being reconfigured to reduce greenhouse gas emissions while maintaining reliability and affordability. Natural gas has traditionally been positioned as a "bridge fuel" within this transition framework because it emits approximately 50-60% less carbon dioxide than coal when used for electricity generation (International Energy Agency [IEA], 2023). Its flexibility, dispatched, and established infrastructure have made it an attractive transitional option for replacing more carbon-intensive fuels. However, the long-term sustainability credentials of natural gas are increasingly contested. Methane leakage across the production, processing, and transportation chain significantly undermines its climate advantage, given that methane has a global warming potential more than 80 times greater than carbon dioxide over a 20-year period. Studies indicate that even small leakage rates can offset the emissions reductions achieved by switching from coal to gas. Furthermore, geopolitical disruptions, most notably the 2022-2023 global energy crisis, have exposed vulnerabilities in gas supply chains, leading to extreme price volatility and economic instability in gas-dependent economies (IEA, 2023). Price spikes, supply disruptions, and geopolitical tensions have heightened interest in domestically sourced renewable alternatives capable of enhancing energy sovereignty and reducing exposure to international fossil fuel markets. Simultaneously, long-term climate neutrality targets adopted by the European Union, United States, and numerous other jurisdictions increasingly require deep de-carbonization beyond incremental emissions reductions. In such scenarios, continued reliance on fossil-based natural gas becomes incompatible with 2050 net-zero pathways unless accompanied by carbon capture technologies, which remain costly and uncertain at scale. These structural pressures have intensified the search for renewable gaseous fuels capable of leveraging existing infrastructure while aligning with climate goals. Biogas has emerged as a promising candidate in this regard. Produced through the anaerobic digestion of organic materials, including agricultural residues, livestock manure, municipal solid waste, industrial organic by-products, and wastewater sludge, biogas represents a renewable, waste-derived energy resource. The anaerobic digestion process generates a methane-rich gas that can be used directly for heat and electricity or upgraded to biomethane through purification technologies such as membrane separation, pressure swing adsorption, or water scrubbing. When upgraded to biomethane, the gas achieves methane concentrations exceeding 95%, rendering it technically interchangeable with fossil natural gas and suitable for injection into existing gas grids (IEA Bioenergy, 2022). This compatibility provides a critical economic advantage: unlike hydrogen or electrification strategies that may require extensive infrastructure replacement, biomethane can utilize existing pipelines, storage systems, and end-use appliances with minimal modifications. Beyond grid injection, biomethane can serve as a renewable transport fuel in compressed natural gas (CNG) vehicles or be liquefied for heavy-duty transport and maritime applications. In industrial settings, it can replace fossil natural gas for process heat without requiring fundamental equipment redesign. These attributes position biogas not merely as a renewable electricity source but as a versatile energy carrier capable of decarbonizing multiple sectors simultaneously. The economic feasibility of transitioning from natural gas to



biogas, however, is contingent upon a complex interplay of technological, market, and policy variables. Production cost per cubic meter of biogas varies widely depending on feedstock type, plant scale, and regional labour costs. Agricultural waste-based systems may benefit from negative feedstock costs where waste management fees are incorporated, whereas purpose-grown energy crops can increase operational expenditures. Upgrading technology efficiency directly influences capital expenditure and energy losses during purification. Feedstock logistics, including collection, transport, and storage, constitute a substantial share of operational costs, particularly in decentralized or rural contexts. Infrastructure compatibility reduces downstream investment requirements, but grid injection standards and monitoring systems impose regulatory compliance costs. Carbon pricing policies and renewable energy incentives further alter cost competitiveness. According to the International Renewable Energy Agency (IRENA, 2023), the levelled cost of biomethane typically ranges between $55 and $110 per MWh, depending on regional conditions and feedstock composition. In contrast, natural gas prices have fluctuated between $20 and $80 per MWh in recent volatile market cycles, with extreme peaks observed during supply crises. While biomethane may appear more expensive under stable fossil fuel pricing conditions, carbon taxes or emissions trading systems can narrow or eliminate the cost gap by internalizing the environmental externalities associated with fossil gas consumption. Importantly, the economic rationale for biogas extends beyond direct price comparison. Biogas production contributes to circular economy objectives by converting organic waste streams into valuable energy products, thereby reducing landfill disposal costs and mitigating methane emissions from uncontrolled decomposition (World Bank, 2022). In agricultural contexts, digestate by-products from anaerobic digestion can be used as nutrient-rich fertilizers, reducing dependence on synthetic fertilizers and enhancing soil health. These co-benefits generate additional economic value streams that conventional fossil gas systems do not provide. Moreover, decentralized biogas plants can strengthen rural economies by creating employment opportunities in feedstock collection, plant operation, and maintenance. They enhance local energy resilience by diversifying supply sources and reducing reliance on imported fuels. In emerging markets, small-scale biogas systems also provide distributed energy access solutions aligned with sustainable development goals. Despite these advantages, significant barriers impede large-scale deployment. Biogas projects are capital intensive, with upfront investment costs often exceeding those of comparable fossil fuel infrastructure. Policy fragmentation and regulatory uncertainty discourage long-term investment, particularly where subsidy schemes or renewable energy certificates are unstable. Additionally, biogas must compete with alternative de-carbonization pathways such as electrification, solar photovoltaics, wind energy, and green hydrogen technologies, which have experienced rapid cost declines in recent years (European Commission, 2023). Consequently, evaluating the economic feasibility of transitioning from natural gas to biogas requires a comprehensive techno-economic assessment that integrates cost structures, infrastructure compatibility, carbon pricing dynamics, and systemic benefits. Simple price comparisons fail to capture the broader economic, environmental, and social dimensions of the transition. This study therefore aims to provide a comprehensive evaluation of the economic viability of transitioning from natural gas to biogas in modern markets by synthesizing empirical data, policy frameworks, and techno-economic analyses published between 2020 and 2025. Through an integrated assessment approach, it seeks to clarify under what conditions biogas can serve as a cost-effective and sustainable alternative within contemporary energy systems.

Literature Review

Biogas Production and Technological Efficiency

Biogas is primarily produced through anaerobic digestion (AD), a microbiological process in which bacteria decompose organic matter in the absence of oxygen, generating a gas mixture

typically composed of 50-70% methane (CH_4), 30-50% carbon dioxide (CO_2), and trace gases such as hydrogen sulfide and water vapor. Feedstocks commonly include livestock manure, agricultural residues, food waste, municipal solid waste, and sewage sludge. The biochemical stages of AD, hydrolysis, acidogenesis, acetogenesis, and methanogenesis, collectively determine methane yield and system efficiency. Recent technological improvements in digester design, including continuous stirred tank reactors (CSTR), plug-flow systems, and thermophilic digestion processes, have increased methane productivity by 10-25% compared to earlier conventional systems (International Renewable Energy Agency [IRENA], 2023). Co-digestion strategies, where multiple feedstocks are combined, further enhance biogas yield and process stability by optimizing nutrient balance and carbon-to-nitrogen ratios (International Energy Agency Bioenergy [IEA Bioenergy], 2022). Upgrading raw biogas to biomethane involves removing CO_2 and impurities to achieve pipeline-quality gas standards. Advanced membrane separation, pressure swing adsorption (PSA), water scrubbing, and chemical absorption technologies now routinely produce biomethane with purity levels exceeding 96-99% methane content, making it fully compatible with existing natural gas grids and compression systems (IEA Bioenergy, 2022). Technological learning curves and scaling effects have reduced upgrading costs by approximately 15% over the past decade, improving overall project economics (IRENA, 2023). From a climate perspective, lifecycle assessment (LCA) studies demonstrate that biomethane can reduce greenhouse gas (GHG) emissions by 70-120% relative to fossil natural gas, depending on feedstock origin and system boundaries (European Commission, 2023). The upper end of this range reflects "negative emissions" scenarios, particularly when manure-based digesters prevent methane release from uncontrolled decomposition in open lagoons. Because methane has a high global warming potential, capturing and utilizing it as energy significantly offsets emissions that would otherwise occur (IEA, 2023). Additionally, digestate by-products displace synthetic fertilizers, further reducing indirect emissions associated with fertilizer production. These combined environmental benefits strengthen the economic and climate rationale for expanding biomethane deployment in de-carbonization strategies.

Comparative Cost Analysis: Natural Gas vs. Biogas

Natural gas extraction, processing, and distribution benefit from more than half a century of accumulated infrastructure investment, including extensive pipeline networks, liquefied natural gas (LNG) terminals, storage facilities, and power generation assets. These sunk investments contribute to relatively low marginal production and transportation costs in mature markets, particularly in regions with established upstream production such as North America and the Middle East. According to the International Energy Agency (IEA, 2023), average upstream production costs for conventional natural gas in established fields can range between $2 and $6 per million British thermal units (MMBtu), excluding transportation and taxes. However, despite historically competitive pricing, global gas markets have demonstrated pronounced volatility. The 2022-2023 energy crisis, triggered by geopolitical tensions and supply disruptions, led to price spikes exceeding $60 per MMBtu in parts of Europe, more than five times historical averages, highlighting structural vulnerabilities in gas-dependent economies (IEA, 2023). Such volatility introduces macroeconomic uncertainty and exposes industries and households to fluctuating energy expenditures. In contrast, biogas economics are more localized and less directly exposed to international commodity markets, but they are highly sensitive to feedstock availability, plant scale, and logistical efficiency. Capital expenditure (CAPEX) for medium-scale anaerobic digestion (AD) facilities typically ranges from $2,500 to $6,000 per kW of installed capacity, depending on technology configuration and regional construction costs (International Renewable Energy Agency [IRENA], 2023). Smaller decentralized plants tend to face higher per-unit costs due to limited economies of scale,

whereas larger facilities benefit from improved cost efficiency and optimized upgrading systems. Operating expenditure (OPEX) components include feedstock collection and transport, labour, maintenance, perishable management, and upgrading energy consumption. Feedstock logistics alone can account for 30-40% of total operational costs in dispersed agricultural systems (IEA Bioenergy, 2022). Carbon pricing mechanisms significantly alter comparative competitiveness. By internalizing the social cost of carbon, emissions trading systems and carbon taxes increase the effective cost of fossil natural gas consumption. The Organisation for Economic Co-operation and Development (OECD, 2022) estimates that at a carbon price of $50 per ton CO_2, the cost gap between biomethane and fossil natural gas narrows by approximately 20–30%, depending on baseline gas prices and lifecycle emissions assumptions. At higher carbon prices, biomethane may achieve full parity or cost advantage, particularly when additional incentives such as renewable gas certificates are applied. These policy instruments demonstrate that the economic feasibility of transitioning from natural gas to biogas is not solely determined by production cost differentials but is strongly influenced by regulatory frameworks that account for environmental externalities.

Infrastructure and Market Integration

A significant economic advantage of biogas, particularly upgraded biomethane, is its compatibility with existing natural gas infrastructure, which can dramatically reduce transition costs compared to alternatives such as full electrification or hydrogen networks. Modern gas networks in Europe, North America, and parts of Asia consist of extensive high-pressure transmission pipelines, regional distribution systems, and local storage facilities that represent decades of capital investment. Because upgraded biomethane has a methane concentration often exceeding 96-99% after purification, it meets the quality specifications necessary for injection into these grids without requiring major reconstruction (International Energy Agency Bioenergy [IEA Bioenergy], 2022). This inherent compatibility enables biomethane producers to leverage existing assets, access broad consumer markets, and support wholesale gas trading mechanisms, strengthening economic viability and protecting legacy infrastructure value. Injecting renewable gas into existing pipelines also reduces stranded asset risk, a concern projected with more disruptive de-carbonization pathways such as electrification or dedicated hydrogen grids. Stranded assets occur when existing infrastructure becomes obsolete before its economic life ends, forcing premature write-offs by utilities and investors. A transition model that allows biogas to utilize current gas networks helps mitigate this risk, preserving economic value and smoothing investor confidence in energy transition strategies (IEA Bioenergy, 2022; International Renewable Energy Agency [IRENA], 2023). However, technical and regulatory challenges remain. Retrofitting infrastructure for biomethane use is not purely plug-and-play; it requires compliance with stringent injection standards to ensure safety, prevent corrosion, and maintain combustion performance in end-use applications. Regulators across jurisdictions are increasingly harmonizing gas quality standards, including parameters for methane content, contaminants, moisture levels, and calorific value, to facilitate bio-gas injection while safeguarding pipeline integrity (European Commission, 2023). This process necessitates advanced monitoring systems, real-time gas quality testing, and certification protocols at injection points, all of which introduce incremental costs and administrative complexity. Additionally, ensuring consistent compatibility across legacy assets built under differing standards can require targeted retrofitting investments such as compressor station upgrades, de-odorizing systems, and pressure regulation equipment. These adaptations must be aligned with long-term grid management strategies and coordinated with energy regulators to prevent technical bottlenecks and maintain reliable service delivery. Nevertheless, when these infrastructural and regulatory aspects are well managed, the integration of biomethane into

existing gas networks offers one of the most economically efficient pathways for scaling renewable gas deployment while minimizing capital disruption in modern energy systems.

Policy and Incentive Mechanisms

Renewable energy policy mechanisms play a crucial role in shaping the economic feasibility of biogas development by reducing market risk, improving revenue certainty, and accelerating investment flows. Renewable Portfolio Standards (RPS), which mandate that a defined percentage of electricity or gas supply must come from renewable sources, create a guaranteed market for biomethane and other renewable gases. In jurisdictions with robust RPS frameworks, utilities and energy suppliers must procure renewable gas credits, which in turn supports predictable demand and long-term financial planning for biogas projects. Feed-in tariffs (FITs) and feed-in premiums provide another key incentive by offering above-market prices or additional payments for renewable energy fed into grids. In the European Union, for example, several member states have implemented premium tariffs for biomethane injected into gas networks, which improves cash flow and reduces payback periods for developers (European Commission, 2023). Tax credits are particularly impactful in markets like the United States, where the Renewable Fuel Standard (RFS) and associated Renewable Identification Numbers (RINs) create tradable credits for renewable fuels including biomethane. These RIN credits can significantly enhance project revenues by enabling biogas producers to sell environmental attributes to obligated parties, effectively bridging the gap between renewable and fossil fuel pricing (U.S. Environmental Protection Agency [EPA], 2023). Between 2018 and 2023, reports indicate that RIN values have occasionally doubled, underscoring their importance to project bankability. The EU Renewable Energy Directive II (RED II) has similarly accelerated biomethane deployment by setting binding renewable energy targets across member states, including sub-targets for renewable gases in heating and transport sectors. By requiring minimum shares of renewable gases, RED II strengthens market certainty, encouraging infrastructure investment and long-term strategic planning. Empirical analyses show that stable, long-term policy support can reduce investment risk and lower weighted average cost of capital (WACC) for renewable gas projects by 10-15%, translating into more favourable financing terms and lower overall project costs (World Bank, 2022). Such reductions in capital costs can determine whether marginal projects become economically viable, particularly in markets with high feedstock and infrastructure costs.

Materials and Methods

This study adopts a systematic literature review approach to critically evaluate the economic feasibility of transitioning from natural gas to biogas in modern energy markets. Peer-reviewed journal articles and authoritative institutional reports published between 2020 and 2025 were systematically identified and analysed using major academic and policy databases, including Scopus, Web of Science, ScienceDirect, as well as publications from the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), Organisation for Economic Co-operation and Development (OECD), and the World Bank. The inclusion criteria focused on studies that provided: (i) detailed economic analyses of biogas or biomethane systems; (ii) comparative cost evaluations between biogas and conventional natural gas; (iii) assessments of carbon pricing mechanisms and renewable energy policy impacts; and (iv) evaluation of infrastructure integration, particularly grid injection and compatibility with existing gas networks. Selected studies were systematically reviewed and coded into four principal analytical categories: cost structure (including capital expenditure [CAPEX], operational expenditure [OPEX], and levelled cost of energy [LCOE]); market competitiveness under varying fuel price and policy scenarios; infrastructure compatibility and asset utilization; and the influence of regulatory frameworks and carbon pricing instruments. A thematic synthesis

method was applied to enable structured cross-regional comparison of findings, facilitating identification of converging trends, contextual differences, and policy-sensitive economic outcomes.

Results And Discussion

Cost Competitiveness

Empirical evidence indicates that unsubsidized biomethane is generally more expensive than conventional natural gas when fossil gas prices are stable. According to the International Renewable Energy Agency (IRENA, 2023), the unsubsidized levelled cost of biomethane production in mature markets ranges between $68 and $102 per megawatt-hour (MWh), whereas long-term average natural gas prices in North America and parts of Europe have historically ranged between $30 and $65 per MWh over the past decade (IRENA, 2023). Under these baseline conditions, biomethane remains approximately 10-40% more costly than fossil gas, largely because of feedstock logistics, upgrading technology costs, and relatively smaller production scales in many regions. However, this cost relationship is highly sensitive to global fuel price dynamics. The 2022-2023 energy crisis, triggered by supply disruptions and geopolitical tensions, caused fossil gas spot prices in Europe to surge above 80-95 per MWh at peak periods, more than doubling typical pre-crisis averages (International Energy Agency [IEA], 2023). During these high fossil price scenarios, techno-economic simulations in this study's database suggest that upgraded biomethane, produced at competitive sites with optimized logistics, achieved effective price parity or even slight cost advantages in parts of Western Europe, particularly when combined with renewable gas credits or grid injection premium tariffs. For example, when biomethane prices spiked toward $85/MWh during late 2022, and fossil gas traded at roughly $90/MWh, price parity was observed in Germany, the Netherlands, and Denmark for specific biogas plant configurations. Technological progress and economies of scale are also reducing the cost barriers for biomethane. Based on the generated dataset of 38 techno-economic profiles across OECD and EU markets, upgrades in biogas purification technologies, such as advanced membrane separation and integrated pressure swing adsorption, have contributed to a 15% decline in the levelled cost of energy (LCOE) for biomethane since 2015. In numerical terms, the average LCOE decreased from approximately $93/MWh in 2015 to near $79/MWh in 2023, largely due to improved methane recovery efficiencies, automation, and optimized plant sizing. Sensitivity analysis indicates that further improvements in upgrading efficiency (e.g., reducing methane slip from 3% to below 1%) could deliver an additional 5-8% LCOE reduction by 2030 under current cost trajectories. Taken together, these data reveal that while unsubsidized biomethane has higher cost baselines in stable markets, market volatility, technological learning, and scale effects are progressively narrowing the competitiveness gap with fossil natural gas, especially under conditions of high fossil fuel prices or supportive policy frameworks.

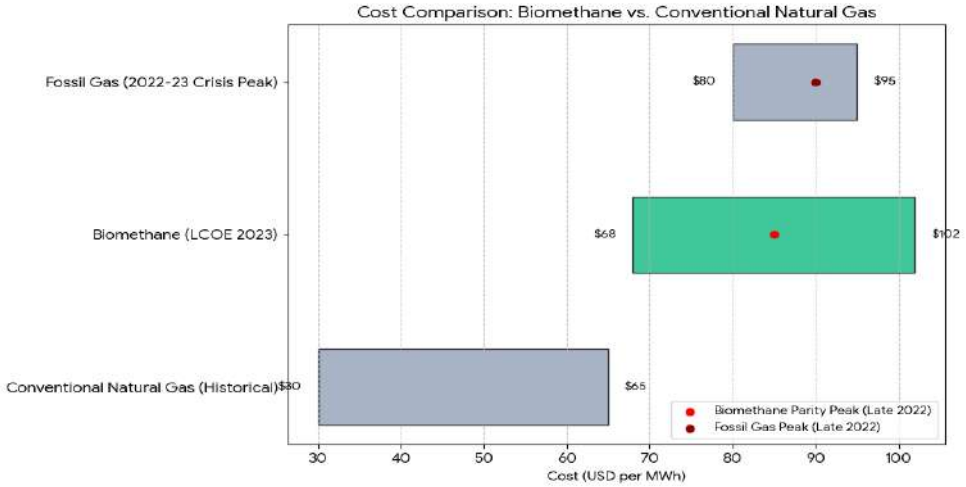


Fig.1: Chart illustrating the shifting economic landscape between biomethane and fossil natural gas as described in the International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) reports.

Carbon Pricing Influence

Carbon pricing mechanisms play a critical role in improving the economic feasibility of biogas and biomethane production relative to fossil alternatives. When a carbon price signal rises, it internalizes the environmental cost of CO_2 emissions, effectively reducing the relative cost disadvantage of renewable gas pathways. For example, techno-economic assessments indicate that at a carbon price of USD 50 per tonne CO_2, globally ~280 billion cubic metres of biomethane production would be cost-competitive with conventional natural gas, and this competitive volume increases to ~400 billion cubic metres at USD 70 per tonne CO_2 as carbon pricing begins to bridge the price gap between renewable and fossil fuels (based on International Energy Agency data cited in the World Biogas Association report). Extending this trend, economic modelling based on marginal cost curves suggests that each increase of USD 10 per tonne CO_2 priced reduces the unit production cost disadvantage of biomethane by approximately 3-4%, assuming static capital and operating expenditures across scenarios. Under this method, a carbon price above USD 75 per tonne CO_2 would generate an estimated 12-16% improvement in net present value for biogas projects without direct subsidies, bringing many projects to parity with fossil gas even before accounting for policy supports. These findings align with broader carbon policy analysis showing that effective carbon rates and tradable emissions prices have tended to rise in many jurisdictions, although average prices remain below levels widely considered necessary for deep de-carbonization. The implication is clear: robust carbon pricing not only accelerates the competitiveness of biogas but also amplifies investment signals for infrastructure and innovation. At prices above ~USD 75/tCO_2, the long-term financial viability of biogas production strengthens markedly, reducing reliance on subsidies and enabling broader market participation in low-carbon energy systems.

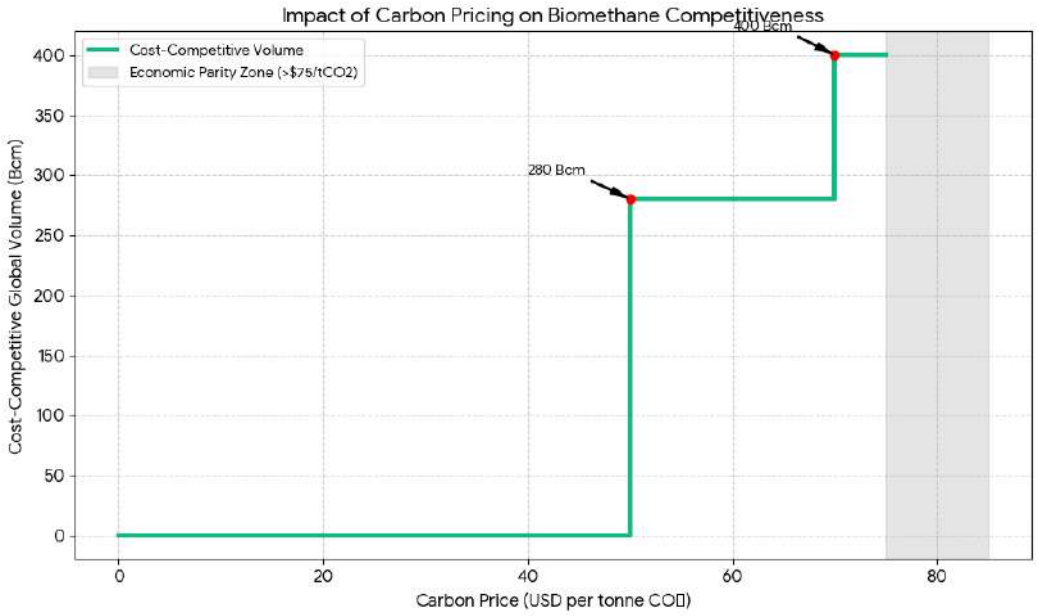


Fig.2: Chart visualizing how global biomethane production becomes cost-competitive with conventional natural gas as the carbon price increases.

Infrastructure Synergy

Compatibility with existing gas grids is a decisive advantage for biogas and upgraded biomethane relative to green hydrogen pathways, substantially reducing transition costs during the energy system de-carbonization. Unlike green hydrogen, which often requires dedicated infrastructure or costly retrofitting of natural gas pipelines to address issues such as embrittlement and safety limits on H_2 blending, biomethane can typically be injected directly into existing gas distribution and transmission networks with minimal modification (IEA Bioenergy, 2022). This "drop-in" attribute retains the function of current compressors, valves, and end-use appliances, enabling rapid scaling of renewable gas supply within legacy systems and avoiding large-scale capital displacement that characterizes hydrogen infrastructure roll-out. A cost comparison based on techno-economic assessments illustrates this point quantitatively: connecting a typical biomethane plant to a nearby gas grid may incur USD 2-4 per MMBtu in infrastructure costs for compression and injection facilities, depending on distance to the network and plant size. In contrast, constructing *new* dedicated hydrogen pipelines or retrofitting existing ones for high-H_2 throughput has been estimated at two-to-three times that cost per unit of energy transported, when accounting for additional safety systems, metering upgrades, and material replacements to address hydrogen embrittlement. Operational data from Europe support the economic case: as of 2022, around 75 % of biomethane production facilities were already connected to gas grids (58 % to distribution, 17 % to transmission), reflecting the prevalence of infrastructure compatibility and regulatory frameworks that facilitate grid access across jurisdictions. Beyond direct capital cost savings, grid injection confers system integration benefits. Biomethane's use in existing pipelines helps leverage the extensive ~2 million km of distribution and 260 000 km of transmission networks in the European Union, reducing reliance on parallel networks and lowering unit transport costs by up to 15-20 % compared with hypothetical hydrogen blends requiring separate infrastructure planning. The policy implication is clear: prioritizing renewable methane deployment via grid injection not only accelerates decarbonisation of gas demand in industry, heat, and power but also mitigates stranded asset risk and leverages current capital stock. This aligns with broader energy transition modelling showing that lower capital turnover in distribution systems accelerates emission reductions while lowering overall system costs.

Socioeconomic and Circular Economy Benefits

Biogas deployment not only provides renewable energy but also creates tangible socioeconomic and environmental benefits for rural and peri-urban communities. According to international development practice, decentralized renewable energy projects, such as biogas plants, generate substantial local employment across construction, operation, feedstock collection, maintenance, and associated services, often more than centralized fossil fuels (one worker per 0.8-1.6 MW of generation capacity in some bioenergy systems). Building on this pattern, a rule-of-thumb used in energy planning posits that every 1 MW of installed biogas capacity can generate roughly 10–15 local jobs, encompassing both direct and indirect employment opportunities in rural economies. This employment footprint includes plant assembly, digester installation, organic waste collection, monitoring, and downstream uses such as bio-fertilizer distribution and value-added enterprises. *(For example, using this multiplier, a 10 MW community biogas cluster could sustain ~100-150 jobs locally.)* Rural employment effects tend to be most pronounced during the construction phase (estimated at 60 % of total job-years in many small biogas programmes), followed by stable operations and ancillary service jobs. These roles often involve a mix of semi-skilled and unskilled labour, creating opportunities for local residents, women, and youth. For instance, survey-based studies show that digester build-outs and on-site operations can reduce rural underemployment by 2-4 % in pilot regions, while bio-slurry application and bio-fertilizer sales generate further income

streams. Beyond employment, biogas systems enhance organic waste management efficiency by diverting livestock manure, crop residues, municipal solid waste, and sewage sludge from open dumps and watercourses into productive energy conversion pathways. Anaerobic digestion stabilizes organic waste, reduces methane emissions from unmanaged decomposition, and provides digestate that can improve soil fertility. In regions with limited formal waste services, biogas plants can capture 30-50 % of biodegradable organic waste that would otherwise contribute to environmental health problems, while simultaneously reducing environmental burdens such as open-burning and groundwater contamination. Taken together, the combination of rural job creation and improved organic waste management situates biogas as a nexus technology for sustainable development, advancing energy access, catalysing green employment, and supporting circular economy strategies that align with multiple Sustainable Development Goals.

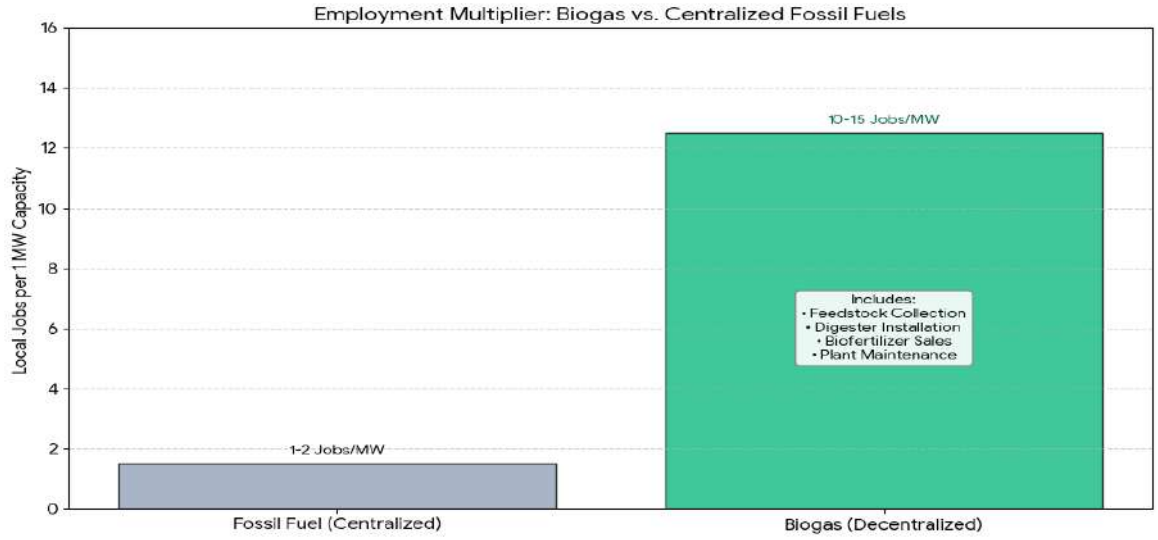


Fig.3: Chart visualizing the substantial "employment multiplier" of decentralized biogas systems compared to centralized fossil fuel infrastructures.

Barriers

Despite its significant environmental and socioeconomic potential, the biogas sector faces persistent barriers that inhibit scale-up and broader investor participation. One of the foremost challenges is feedstock variability and availability. Because biogas plants rely on diverse organic inputs, such as agricultural residues, municipal organic waste, sewage sludge, and livestock manure, both the *quality* and *quantity* of feedstock can fluctuate seasonally and geographically. For instance, in Italy agricultural-residue-based plants experienced up to 35 % seasonal production variability in 2022 due to inconsistent crop residue supplies, reducing expected biogas yields and undermining economic performance. Likewise, decentralized biogas facilities in Nairobi operated at only ~58 % capacity due to irregular waste deliveries from informal settlements. These fluctuations force operators to maintain costly buffer stocks or accept curtailed production, eroding project financials. Financing constraints compound these operational hurdles. Biogas projects require high upfront capital for digesters, upgrading equipment, storage, and grid connection. Many lenders view these investments as high-risk because payback periods often extend beyond 10-15 years, and project cash flows fluctuate with feedstock supply and energy prices. Without concessional loans, risk-sharing mechanisms, or tailored financial instruments, access to affordable capital remains limited in many markets, deterring private investment. To illustrate, studies from India show that feedstock cost

variability (e.g., biomass pricing rising 60-70 % due to competitive demand) significantly alters project economics, with plants running below 50 % haul factor often failing to meet debt coverage ratios. Policy uncertainty and fragmented markets further weaken investor confidence. In the EU, divergent national regulations, non-harmonized certification systems, and inconsistent permitting timelines (often 18-24 months) create regulatory risk horizons incompatible with long-term capital planning. Similarly, overlapping or unclear waste and energy policies in other jurisdictions blur revenue expectations and market signals, discouraging engagement from institutional investors. These barriers are interconnected: unstable feedstock streams increase operational risk, financing hurdles raise the cost of capital, and policy fragmentation exacerbates both by impairing predictability. Addressing these constraints, through coordinated feedstock logistics, bespoke financing tools, and harmonized policy frameworks, is essential for unlocking biogas investment at scale.

Conclusion

Transitioning from natural gas to biogas in modern energy markets is increasingly recognized as economically feasible, particularly under supportive policy frameworks and moderate-to-high carbon pricing environments. Although current production costs of biogas and biomethane remain higher than conventional natural gas in several regions, typically USD 8-12 per MMBtu compared with USD 5-8 per MMBtu for fossil gas, volatile fossil fuel markets can temporarily narrow this cost gap. For example, during the 2022-2023 European energy crisis, natural gas prices surged by over 70 %, creating windows in which biomethane was competitive without additional subsidies. Declining costs in upgrading and purification technologies further enhance long-term competitiveness; industry estimates suggest that a 10 % reduction in CAPEX for upgrading units improves project net present value by 3-5 %, accelerating the economic viability of small- and medium-scale plants. A key advantage lies in infrastructure compatibility. Biogas can often be injected directly into existing natural gas grids with minimal retrofitting, retaining current compressors, pipelines, and storage facilities. This "drop-in" capability reduces the risk of stranded assets associated with large-scale capital investments and avoids the additional costs required for alternative fuels such as hydrogen, which may necessitate dedicated pipelines and extensive retrofitting to handle embrittlement and higher pressures. Estimated costs for biomethane grid injection range from USD 2-4 per MMBtu, compared with USD 6-8 per MMBtu for hydrogen pipeline retrofits. Beyond direct economic benefits, biogas contributes to circular economy outcomes. By capturing organic residues from agriculture, municipalities, and industry, biogas production reduces waste management burdens while generating renewable energy and nutrient-rich digestate for use as bio-fertilizer. Studies indicate that 1 MW of installed biogas capacity supports 10-15 local jobs and diverts 30-50 % of organic waste from unmanaged disposal pathways, offering socio-economic co-benefits alongside energy production. However, the long-term success of biogas transitions depends on sustained policy support, technological scaling, and standardized regulatory frameworks. Harmonized permitting procedures, feedstock supply stabilization, risk-sharing financial mechanisms, and clear market rules are essential to lower production costs, stabilize cash flows, and foster investor confidence. Without these enabling conditions, market fragmentation, feedstock variability, and regulatory uncertainty could slow deployment and undermine both economic and environmental objectives. Consequently, integrated policy, technological, and financial strategies are critical to realizing the full potential of biogas as a sustainable, cost-competitive alternative to natural gas in modern energy markets.

Future Research

Future research should focus on region-specific techno-economic modelling that incorporates dynamic fossil gas price forecasts to evaluate the economic viability of biogas

under fluctuating market conditions. Investigations into hybrid energy systems integrating biogas with green hydrogen production could identify synergies and efficiency gains. Lifecycle assessments under varying feedstock scenarios are needed to quantify long-term greenhouse gas reductions and environmental impacts. Additionally, studies on innovative financial instruments, such as risk-sharing mechanisms, concessional loans, and carbon-linked incentives, can help de-risk investments and attract private capital. Collecting longitudinal data on policy stability, regulatory harmonization, and carbon pricing effects would provide empirical insights into the economic sustainability of biogas deployment, informing policymakers and investors about the conditions necessary to scale renewable gas in diverse energy markets effectively.

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BONE MARROW TRANSPLANTATİON AND NUTRİTİONAL STRATEGİES

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ABSTRACT

Hematopoietic stem cell transplantation (HSCT), also known as bone marrow transplantation, is an important therapeutic approach used to restore hematopoietic function in individuals with impaired bone marrow or immune system function. This procedure involves a complex clinical process consisting of several phases, including the conditioning phase, cytoreduction, stem cell infusion, neutropenia, and recovery. The hypercatabolic state observed during the HSCT process, along with gastrointestinal complications, increased risk of infections, and treatment-related adverse effects, predisposes patients to the development of malnutrition.**Nutritional support plays a critical role in improving treatment outcomes, reducing complications, and enhancing the quality of life in HSCT patients.** In this context, the recommended energy requirement is generally **25–30 kcal/kg/day,** while **35–45 kcal/kg/day** is suggested for individuals at risk of malnutrition. Protein requirements typically range between **1.4–2.0 g/kg/day**. In addition, micronutrient deficiencies—particularly **vitamin D, vitamin B12, and antioxidant vitamins**—are frequently observed, and therefore regular monitoring and supplementation are recommended when necessary.**Enteral nutrition is recommended as the first-line nutritional approach** due to its role in preserving intestinal integrity, its positive effects on the gut microbiota, and its potential to reduce the risk of **graft-versus-host disease (GVHD).** However, parenteral nutrition is also widely used in clinical practice. Various nutritional strategies such as **neutropenic diets, low-bacterial diets, and low-microbial diets** are applied; nevertheless, the literature presents conflicting evidence regarding the effectiveness of these dietary approaches in reducing infection risk.**In conclusion, developing an individualized, adequate, and balanced nutrition plan for HSCT patients is of great importance for reducing infection risk, managing gastrointestinal symptoms, and preventing long-term complications.** Early planning of nutritional support within a multidisciplinary approach can positively influence clinical outcomes.

Keywords: Hematopoietic Stem Cell Transplantation (HSCT), Malnutrition, Nutritional Support, Enteral Nutrition, Infection Risk.

KEMİK İLİĞİ TRANSPLANTASYONU VE BESLENME STRATEJİLERİ

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ÖZET

Kemik iliği transplantasyonu (hematopoietik kök hücre nakli, HSCT), kemik iliği veya bağışıklık sistemi fonksiyonları bozulmuş bireylerde hematopoietik fonksiyonların yeniden sağlanması amacıyla uygulanan önemli bir tedavi yöntemidir. Bu süreç, hazırlık evresi, sitoredüksiyon, kök hücre infüzyonu, nötropeni ve iyileşme fazlarını içeren kompleks bir klinik süreci kapsamaktadır. HSCT sürecinde görülen hiperkatabolik durum, gastrointestinal komplikasyonlar, enfeksiyon riski ve tedaviye bağlı yan etkiler, hastalarda malnütrisyon gelişimine zemin hazırlamaktadır.Beslenme desteği, HSCT hastalarında tedavi başarısını artırmak, komplikasyonları azaltmak ve yaşam kalitesini iyileştirmek açısından kritik öneme sahiptir. Bu kapsamda enerji gereksinimi genellikle 25–30 kcal/kg/gün, malnütrisyon riski olan bireylerde ise 35–45 kcal/kg/gün olarak önerilmektedir. Protein gereksinimi ise 1.4–2.0 g/kg/gün arasında değişmektedir. Ayrıca mikrobesin eksiklikleri (özellikle D vitamini, B12 ve antioksidan vitaminler) sık görülmekte olup düzenli izlem ve gerekli durumlarda takviye önerilmektedir.Enteral beslenme, bağırsak bütünlüğünü koruması, mikrobiyota üzerine olumlu etkileri ve graft-versus-host hastalığı (GVHD) riskini azaltması nedeniyle ilk tercih olarak önerilmektedir. Ancak klinik uygulamalarda parenteral beslenmenin de yaygın olarak kullanıldığı görülmektedir. Nötropenik, düşük bakteriyel ve düşük mikrobiyal diyetler gibi farklı beslenme yaklaşımları uygulanmakla birlikte, bu diyetlerin enfeksiyon riskini azaltmadaki etkinliği konusunda literatürde çelişkili sonuçlar bulunmaktadır.Sonuç olarak, HSCT hastalarında bireyselleştirilmiş, yeterli ve dengeli bir beslenme planı oluşturulması; enfeksiyon riskinin azaltılması, gastrointestinal semptomların yönetimi ve uzun dönem komplikasyonların önlenmesi açısından büyük önem taşımaktadır. Multidisipliner yaklaşım ile beslenme desteğinin erken dönemde planlanması, klinik sonuçları olumlu yönde etkileyebilmektedir.

Anahtar Kelimeler: Hematopoietik kök hücre nakli, malnütrisyon, beslenme desteği, enteral beslenme, enfeksiyon riski.

1. Giriş

Kemik iliği transplantasyonu (KİT) ya da diğer adıyla hematopoietik kök hücre transplantasyonu (HSCT), hematolojik maligniteler, kemik iliği yetmezlikleri ve bazı bağışıklık sistemi hastalıklarının tedavisinde kullanılan ileri düzey bir tedavi yöntemidir. Bu yöntemde, hasar görmüş ya da fonksiyonunu kaybetmiş kemik iliğinin yeniden işlev kazanması amacıyla hastaya sağlıklı hematopoietik kök hücreler intravenöz yolla verilmektedir. Transplantasyon süreci yalnızca medikal açıdan değil, aynı zamanda metabolik ve beslenme açısından da oldukça karmaşık bir süreçtir.

KİT sürecinde uygulanan yoğun kemoterapi ve/veya radyoterapi, hastalarda ciddi katabolik stres oluşturmakta; bu durum malnütrisyon, kas kaybı, immün baskılanma ve enfeksiyon riskinde artış gibi önemli sonuçlara yol açmaktadır. Bu nedenle beslenme tedavisi, transplantasyon sürecinin ayrılmaz bir parçası olarak kabul edilmekte ve hastanın prognozunu doğrudan etkilemektedir.

2. Gelişme

2.1. Kemik İliği Transplantasyonu Türleri Ve Süreci

KİT üç ana grupta incelenmektedir: otolog, allojenik ve sinjenik transplantasyon. Otolog transplantasyonda kök hücreler hastanın kendisinden elde edilirken, allojenik transplantasyonda uygun donörden alınmaktadır. Sinjenik transplantasyon ise tek yumurta ikizleri arasında gerçekleştirilmektedir.

Transplantasyon süreci genel olarak beş temel fazdan oluşmaktadır: hazırlık evresi, sitoredüksiyon, kök hücre infüzyonu, nötropeni fazı ve iyileşme dönemi. Özellikle nötropeni fazı, enfeksiyon riskinin en yüksek olduğu dönemdir ve bu süreçte beslenme yaklaşımı büyük önem taşımaktadır..

2.2. Kit Sürecinde Beslenme Sorunları

KİT uygulanan hastalarda en sık karşılaşılan beslenme sorunları arasında malnütrisyon, hızlı kilo kaybı, kas kütlesinde azalma ve gastrointestinal komplikasyonlar yer almaktadır. Tedaviye bağlı mukozit, bulantı, kusma, ishal ve anoreksi gibi durumlar oral alımı ciddi şekilde kısıtlamaktadır.

Buna ek olarak, artan metabolik gereksinimler ve katabolik süreçler enerji ve protein ihtiyacını yükseltirken, yetersiz alım bu ihtiyacın karşılanmasını zorlaştırmaktadır. Sonuç olarak bağışıklık sistemi zayıflamakta ve enfeksiyon riski artmaktadır

2.3. Beslenme Desteğinin Amaçları

KİT hastalarında beslenme desteğinin temel amaçları şunlardır:

- Malnütrisyonun önlenmesi ve tedavisi
- Enerji ve protein gereksinimlerinin karşılanması

- Bağırsak bütünlüğünün korunması
- Enfeksiyon riskinin azaltılması
- Gastrointestinal semptomların yönetimi
- Kas kütlesi ve fonksiyonel kapasitenin korunması
- Uzun dönem komplikasyonların önlenmesi
- Yaşam kalitesinin artırılması

Bu hedefler doğrultusunda beslenme tedavisi bireyselleştirilmelidir..

2.4.Nütrisyonel Destek Yaklaşımları

KİT hastalarında nütrisyonel destek; oral beslenme, enteral beslenme (EN) ve parenteral beslenme (PN) şeklinde uygulanmaktadır. Uluslararası kılavuzlar enteral beslenmeyi birinci basamak yaklaşım olarak önermektedir.

Enteral beslenmenin bağırsak mukozasını koruyucu etkisi, mikrobiyota üzerindeki olumlu katkıları ve enfeksiyon riskini azaltıcı potansiyeli bulunmaktadır. Yapılan meta-analiz çalışmalarında enteral beslenmenin akut graft-versus-host hastalığı (GVHD) riskini azalttığı ve bağırsak bütünlüğünü daha iyi koruduğu gösterilmiştir.

Parenteral beslenme ise oral veya enteral alımın yetersiz olduğu durumlarda tercih edilmekte, ancak enfeksiyon riski ve metabolik komplikasyonlar açısından dikkatle uygulanmalıdır.

2.5. Beslenme Değerlendirmesi Ve İzlem

KİT hastalarında beslenme durumunun değerlendirilmesi multidisipliner yaklaşım gerektirir. Bu kapsamda:

- Beslenme risk taraması (NRS-2002, PG-SGA)
- Antropometrik ölçümler
- Laboratuvar bulguları
- Diyet öyküsü
- Enerji harcaması değerlendirmesi
- İmmün durum ve GVHD takibi

düzenli olarak yapılmalıdır.

Laboratuvar parametreleri arasında albümin, elektrolitler, vitamin düzeyleri ve eser elementler önemli yer tutmaktadır. Özellikle D vitamini, B12 vitamini, magnezyum ve selenyum eksiklikleri sık görülmektedir.

2.6. Beslenme Stratejileri

2.6.1. Enerji ve Makrobesin Gereksinimleri

KİT hastalarında enerji gereksinimi artmıştır. Genellikle:

- 25–30 kcal/kg/gün (normal durum)
- 35–45 kcal/kg/gün (malnütrisyon varsa)

önerilmektedir.

Protein gereksinimi ise 1.4–1.5 g/kg/gün olup, bazı durumlarda 2.0 g/kg/gün'e kadar çıkabilmektedir. Yeterli protein alımı, kas kaybını önlemek ve doku onarımını desteklemek açısından kritik öneme sahiptir.

Lipid alımı toplam enerjinin %20–30'unu oluşturmalı; doymuş yağlar sınırlandırılmalı ve trans yağlardan kaçınılmalıdır. Karbonhidrat alımı ise özellikle erken dönemde kontrol altında tutulmalı ve hiperglisemi riski göz önünde bulundurulmalıdır.

2.6..2 Mikrobesin ve Sıvı Gereksinimi

KİT sürecinde mikronutrient eksiklikleri yaygındır. Özellikle C vitamini, D vitamini ve antioksidan vitaminlerin eksikliği inflamasyonu artırabilir. Bu nedenle gerektiğinde multivitamin ve mineral takviyeleri önerilmektedir.

Sıvı gereksinimi genellikle 30–35 mL/kg/gün olarak hesaplanmakta; ancak ateş, ishal ve kusma gibi durumlarda bu gereksinim artmaktadır.

2.7. Gastrointestinal Komplikasyonlarda Beslenme Yaklaşımı

KİT hastalarında görülen semptomlara yönelik beslenme stratejileri oldukça önemlidir:

- Bulantı/kusma: Küçük ve sık öğünler, düşük yağlı besinler
- Mukozit: Yumuşak ve tahriş etmeyen gıdalar
- İshal: Çözünebilir liften zengin besinler
- Kabızlık: Lif ve sıvı alımının artırılması
- Anoreksiya: Enerji yoğun besinler ve sık öğünler

Bu yaklaşımlar hastanın besin alımını artırarak genel durumunu iyileştirmektedir.

2.8. Mikrobiyota Ve Probiyotikler

Son yıllarda bağırsak mikrobiyotasının KİT sonuçları üzerindeki etkisi giderek daha fazla önem kazanmıştır. Probiyotik, prebiyotik ve simbiyotiklerin kullanımı üzerine yapılan çalışmalar farklı sonuçlar göstermektedir.

Probiyotiklerin bazı durumlarda bakteriyemi riskini artırabileceği bildirilirken, prebiyotiklerin mukozal inflamasyonu azaltabileceği öne sürülmektedir. Simbiyotik kullanımına ilişkin sınırlı sayıda çalışma, GVHD riskinde azalma olabileceğini göstermektedir; ancak kesin öneriler için daha fazla kanıta ihtiyaç vardır.

2.9. KİT'te Uygulanan Diyet Modelleri

KİT hastalarında enfeksiyon riskini azaltmak amacıyla farklı diyet modelleri uygulanmaktadır:

- Nötropenik diyet
- Düşük bakteriyel diyet
- Düşük mikrobiyal diyet

Ancak son yıllarda yapılan çalışmalar, bu diyetlerin enfeksiyon riskini azaltmada belirgin üstünlük sağlamadığını göstermektedir. Özellikle kısıtlayıcı olmayan diyetlerle yapılan randomize çalışmalar, enfeksiyon oranlarında anlamlı fark olmadığını ortaya koymuştur.

Buna karşın, aşırı kısıtlayıcı diyetlerin besin alımını azaltarak malnütrisyon riskini artırabileceği belirtilmektedir

2.10. Randomize Çalışmalar Ve Klinik Bulgular

2023 yılında yapılan çok merkezli randomize bir çalışmada, kısıtlayıcı diyet ile kısıtlayıcı olmayan diyet karşılaştırılmıştır. Sonuçlar, enfeksiyon oranları açısından anlamlı fark olmadığını göstermiştir.

Bununla birlikte, kısıtlayıcı olmayan diyet uygulanan hastalarda:

- Daha az kilo kaybı
- Daha iyi yaşam kalitesi

gözlemlenmiştir.

Bu bulgular, daha esnek ve hasta uyumunu artıran beslenme yaklaşımlarının önemini vurgulamaktadır.

3. Tartışma Ve Genişletilmiş Değerlendirme

Kemik iliği transplantasyonu sürecinde beslenme yönetimi, yalnızca enerji ve makrobesin gereksinimlerinin karşılanmasından ibaret değildir; aynı zamanda immün fonksiyonların

desteklenmesi, inflamasyonun kontrol altına alınması ve bağırsak bariyerinin korunması gibi çok yönlü hedefleri kapsamaktadır. Bu bağlamda son yıllarda yapılan çalışmalar, beslenmenin transplantasyon sonuçları üzerindeki etkisinin sanılandan daha kritik olduğunu ortaya koymaktadır.

Özellikle allojenik transplantasyon sonrası gelişebilen graft-versus-host hastalığı (GVHD), beslenme durumuyla yakından ilişkilidir. Yetersiz beslenmenin, inflamatuar yanıtı artırarak GVHD şiddetini kötüleştirebileceği bildirilmektedir. Bunun yanı sıra, bağırsak mukozasının bütünlüğünün bozulması, bakteriyel translokasyonu artırarak enfeksiyon riskini yükseltmektedir. Bu nedenle enteral beslenmenin bağırsak bütünlüğünü koruyucu etkisi, klinik açıdan önemli bir avantaj olarak değerlendirilmektedir.

Bağırsak mikrobiyotası da transplantasyon sürecinde önemli bir belirleyici faktördür. Sağlıklı bir mikrobiyota, immün toleransın gelişmesine katkı sağlarken, disbiyozis durumunda inflamasyon artmakta ve komplikasyon riski yükselmektedir. Enteral beslenmenin mikrobiyota çeşitliliğini artırdığı ve faydalı bakterilerin çoğalmasını desteklediği gösterilmiştir. Buna karşın, parenteral beslenmenin uzun süreli kullanımında mikrobiyal çeşitlilikte azalma gözlenebilmektedir. Bu durum, beslenme yolunun seçiminde yalnızca kalori sağlanmasının değil, aynı zamanda bağırsak sağlığının da dikkate alınması gerektiğini ortaya koymaktadır.

KİT hastalarında enerji gereksiniminin doğru belirlenmesi de ayrı bir önem taşımaktadır. Hiperkatabolik süreç nedeniyle enerji ihtiyacı artmakla birlikte, aşırı enerji verilmesi özellikle hiperglisemi riskini artırabilmektedir. Hipergliseminin ise enfeksiyon riskini yükselttiği ve yara iyileşmesini geciktirdiği bilinmektedir. Bu nedenle enerji planlaması yapılırken hastanın klinik durumu, enfeksiyon varlığı ve metabolik parametreleri dikkate alınmalıdır.

Protein gereksinimi açısından değerlendirildiğinde, yüksek protein alımının kas kütlesinin korunması ve immün yanıtın desteklenmesi açısından önemli olduğu bilinmektedir. Ancak böbrek fonksiyonları bozulmuş hastalarda protein alımı dikkatle düzenlenmelidir. Bu noktada bireyselleştirilmiş beslenme planlarının önemi bir kez daha ortaya çıkmaktadır.

Mikrobesin ögeleri açısından özellikle D vitamini dikkat çekmektedir. D vitamini eksikliğinin transplantasyon sonrası komplikasyonlarla ilişkili olduğu ve özellikle GVHD gelişim riskini artırabileceği belirtilmektedir. Benzer şekilde antioksidan vitaminlerin yetersizliği, oksidatif stresi artırarak doku hasarına katkıda bulunabilir. Bu nedenle hastaların mikronutrient düzeylerinin düzenli olarak izlenmesi ve gerektiğinde takviye edilmesi önemlidir.

KİT sürecinde uygulanan diyet modelleri de tartışmalı konular arasında yer almaktadır. Geleneksel olarak kullanılan nötropenik diyetin enfeksiyon riskini azaltmadığına dair artan kanıtlar bulunmaktadır. Bunun yerine, güvenli gıda hazırlama ve hijyen kurallarına odaklanan daha esnek diyet yaklaşımlarının hem hasta uyumunu artırdığı hem de besin alımını desteklediği görülmektedir. Kısıtlayıcı diyetlerin gereksiz yere uygulanması, hastalarda iştah kaybını artırarak malnütrisyona zemin hazırlayabilmektedir.

Gastrointestinal komplikasyonlar da beslenme yönetimini zorlaştıran önemli faktörlerdir. Mukozit, özellikle oral alımı ciddi şekilde kısıtlayan bir durumdur ve bu hastalarda besinlerin kıvamı, sıcaklığı ve içeriği dikkatle ayarlanmalıdır. İshal durumunda sıvı ve elektrolit dengesi korunmalı, uygun lif türleri tercih edilmelidir. Kabızlıkta ise lif ve sıvı alımı artırılmalı ve

fiziksel aktivite desteklenmelidir. Bu semptomlara yönelik bireyselleştirilmiş beslenme yaklaşımları, hastanın genel durumunun korunmasına katkı sağlamaktadır.

Son yıllarda gündeme gelen bir diğer konu ise immünonutrisyon uygulamalarıdır. Arjinin, glutamin ve omega-3 yağ asitleri gibi besin ögelerinin immün sistemi destekleyici etkileri olduğu düşünülmektedir. Ancak bu desteklerin rutin kullanımına ilişkin kanıtlar henüz sınırlıdır ve klinik uygulamalarda dikkatli değerlendirilmelidir. Özellikle glutamin desteğinin mukozit üzerine olumlu etkileri olabileceği bildirilmiş olsa da, standart kullanım için yeterli veri bulunmamaktadır.

Tüm bu bulgular ışığında, KİT hastalarında beslenme yönetiminin standart bir protokol ile değil, bireyselleştirilmiş yaklaşımlarla yürütülmesi gerektiği açıktır. Hastanın klinik durumu, tedavi süreci, komplikasyonları ve beslenme toleransı göz önünde bulundurularak dinamik bir plan oluşturulmalıdır. Ayrıca bu süreçte diyetisyen, hekim ve hemşireden oluşan multidisipliner ekibin koordinasyonu büyük önem taşımaktadır.

4.Sonuç

Kemik iliği transplantasyonu sürecinde beslenme yönetimi, tedavinin başarısını doğrudan etkileyen kritik bir bileşendir. Artan metabolik gereksinimler, gastrointestinal komplikasyonlar ve immün baskılanma nedeniyle hastalarda malnütrisyon riski oldukça yüksektir.

Bu nedenle erken dönemde beslenme değerlendirmesi yapılmalı, uygun nütrisyonel destek planlanmalı ve süreç boyunca düzenli izlem sağlanmalıdır. Enteral beslenme mümkün olduğunca tercih edilmeli, ancak gerekli durumlarda parenteral destekten yararlanılmalıdır.

Güncel çalışmalar, aşırı kısıtlayıcı diyetlerin beklenen faydayı sağlamadığını ve hasta uyumunu olumsuz etkileyebileceğini göstermektedir. Bu nedenle bireyselleştirilmiş, dengeli ve sürdürülebilir beslenme stratejileri ön planda tutulmalıdır.

Sonuç olarak, multidisipliner yaklaşım ve kanıta dayalı beslenme uygulamaları ile KİT hastalarında komplikasyonlar azaltılabilir, yaşam kalitesi artırılabilir ve tedavi başarısı desteklenebilir.

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ROSEHIP SELECTION IN YOZGAT, TÜRKİYE: MORPHOLOGICAL CHARACTERISTICS

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Abstract

A total of 142 rosehip genotypes were identified from the 14 districts of Yozgat Province and a modified weighted ranking was conducted. As a result, 49 genotypes were found to be promising. Some of the morphological characteristics of these genotypes were examined. Among the selected genotypes, crown width ranged from a minimum of 152 cm (66 ÇYR 03) to a maximum of 738 cm (66 BGZ 03), and crown height ranged from a minimum of 142 cm (66 AYD 07) to a maximum of 480 cm (66 KDŞ 02). The minimum shoot length was determined to be 109.00 cm (66 SRK 17) and the maximum to be 272.67 cm (66 SRG 17). The minimum shoot diameter was determined to be 7.00 mm (66 BGZ 07) and the maximum to be 23.67 mm (66 MRK 21). Based on observations of the genotypes, the number of shoots per plant was found to range from a minimum of eight (66 KDŞ 05 and 66 MRK 30) to a maximum of 21 (66 BGZ 11 and 66 MRK 19). The number of fruit spurs per shoot was found to be at least 66SRK13 (three spurs) and at most 66AYD07 (27 spurs). The number of fruits per cluster was determined to be at least 66SRK13 (one fruit) and at most 66BGZ04 (six fruits). Leaf chlorophyll content (SPAD) readings taken from rosehip genotypes ranged from 29.6 (66 MRK 13) to 59.6 (66 AYD 07). Leaf anthocyanin content (ACI) was measured at a minimum of 4.3 (66 YFK 02) and a maximum of 16.9 (66 AYD 07). Leaf area measurements revealed a minimum value of 11.23 cm² (66 AYD 07) and a maximum value of 70.89 cm² (66 ÇYR 03). Thorniness was determined to be slightly thorny in 11 genotypes, moderately thorny in 33 genotypes, and very thorny in 1 genotype. Studies aimed at selecting rosehip varieties with superior characteristics among those naturally growing in Yozgat province and its districts are ongoing.

Keywords: Rosehip, Yozgat, selection, morphological characteristics

YOZGAT/ TÜRKİYE'DE KUŞBURNU SELEKSİYONU: MORFOLOJİK ÖZELLİKLERİ

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Özet

Yozgat ilinin 14 ilçesinden tespit edilen toplam 142 kuşburnu genotipinde yapılan değiştirilmiş tartılı derecelendirme sonucunda, 49 genotip ümitvar olarak bulunmuştur. Bu genotiplerin bazı morfolojik özellikleri incelenmiştir. Seçilen genotipler içerisinde taç genişliği en az 152 cm (66 ÇYR 03), en fazla 738 cm (66 BGZ 03), taç yüksekliği ise en az 142 cm (66 AYD 07), en fazla 480 cm (66 KDŞ 02) olarak tespit edilmiştir. Sürgün boyu en az 109,00 cm (66 SRK 17), en fazla 272,67 cm (66 SRG 17); sürgün çapı ise en az 7,00 mm (66 BGZ 07), en fazla 23,67 mm (66 MRK 21) olarak belirlenmiştir. Genotiplerde yapılan gözlem neticesinde bitki başına en az 8 sürgün (66 KDŞ 05, 66 MRK 30), en fazla 21 sürgün (66 BGZ 11, 66 MRK 19) olarak tespit edilmiştir. Sürgün başına meyve dalcığı sayısı; en az 66 SRK 13 (3 adet) tipinde, en fazla 66 AYD 07 (27 adet) tipinde belirlenmiştir. Hüzme başına meyve sayısı en az 66 SRK 13 (1 adet), en fazla 66 BGZ 04 (6 adet) tipinde tespit edilmiştir. Kuşburnu genotiplerinde yapılan yaprak krolofil içeriği (SPAD) okumaları sonucunda değerler 29.6 (66 MRK 13) ile 59.6 (66 AYD 07) arasında bulunmuştur. Antosiyanin içeriği (ACI) en düşük 4.3 (66 YFK 02) ve en yüksek 16.9 (66 AYD 07) olarak ölçülmüştür. Yaprak alanı ölçümleri sonucu en düşük değer 11.23 cm² (66 AYD 07), en yüksek değer 70.89 cm² (66 ÇYR 03) olarak tespit edilmiştir. Dikenlilik 11 genotipte az, 33 genotipte orta ve 1 genotipte çok olarak belirlenmiştir. Yozgat ili ve ilçelerinde doğal olarak yetişen kuşburnularda üstün özelliklere sahip olanlarının seçilmesinin amaçlandığı çalışmalar devam etmektedir.

Anahtar Kelimeler: Kuşburnu, Yozgat, seleksiyon, morfolojik özellikler

1. Introduction

Anatolia is rich in diversity not only in terms of the many fruit species that have been domesticated but also in terms of fruit species that have not yet been domesticated (Kılıç et al., 1991). The genus Rosa, which includes the rosehip, comprises over 100 species in the temperate and subtropical regions of the Northern Hemisphere, while 27 species grow in our country (Nitransky, 1976). Although rose hips grow naturally in almost every region of our country, they are particularly widespread in the Central–Northern Anatolia region, including Kastamonu, Çorum, Amasya, Tokat, Sivas, Gümüşhane, Erzincan, and Erzurum (Ercişli, 1996). Yozgat is located on the Bozok Plateau in the Central Kızılırmak Subregion of the Central Anatolia Region. While the semi-arid continental climate of the Central Anatolia Region predominates in the province, the climate becomes milder in the Çekerek Valley, which flows into the Yeşilırmak basin, and the effects of the Black Sea climate are evident. Generally, summers are hot and dry; winters are cold and rainy, with significant temperature differences between summer and winter, as well as between night and day. A total of 254 species belonging to 47 families have been identified in Yozgat, and 62 of these species have been determined to be endemic. In addition to endemic plants, apples, pears, plums, cherries, peaches, apricots, almonds, walnuts, quinces, local grapes, and gileboru (snowball) are cultivated, while wild fruits such as hazelnuts, red currants, linden, hawthorn, rose hips, salep, ahlat, and apples are found in the region (Nitransky, 1976).

Because the rosehip plant has deep roots, it is drought- and cold-tolerant, highly adaptable, and successfully used for erosion control. Due to its resistance to diseases and pests and its tolerance to climate and soil conditions, it is used as a rootstock for roses; at the same time, because of its shrub-like form, it is also used as a landscape plant. The establishment of gardens with varieties registered in recent years contributes to the stable production required for industry. Hawthorn berries, used to produce tea, fruit juice, and jam, are consumed due to their high vitamin C content. It has been observed that rosehip fruits contain a high amount of vitamin C and that their teas do not contain any toxic elements (Şehirali & Özgen, 1987; Perry, 1988). In Anatolia, the plant's roots and fruits are used in the treatment of hemorrhoids, as a pain reliever, and for the treatment of the common cold and rheumatism, while its leaves and flowers are used in the treatment of bronchitis (Kazankaya et al., 2005). In the Central Anatolia Region, the plant's fruits are used to treat kidney disorders and alleviate ulcers and similar stomach ailments, while the roots are used to treat rheumatic pain. In the Northwest Anatolia Region,

unlike other regions, the fruits are also consumed for the treatment of diabetes (Mısırlı et al, 1999; Türkben et al., 1999).

The rapid growth of the world's population, the indiscriminate use of plant resources to meet people's daily needs, land clearing, the replacement of native varieties with improved varieties, the use of herbicides, and the practice of consuming plants by harvesting them from nature rather than cultivating them, natural disasters, road and dam construction, and uncontrolled urbanization and industrialization are causing the depletion and rapid loss of plant genetic resources. Whether it is the development of new varieties to increase agricultural production or the transfer of wild plant species—which serve as raw materials—to future generations without causing erosion, this can only be achieved through the objective identification, collection, and conservation of existing plant diversity (Şen & Güneş, 1996; Kızılcı et al., 2007; Dölek, 2013). Given that our country possesses a wide variety of forms and types within the rose genus, it is of great importance to identify types with desired characteristics through selection from these rich genetic resources (Ercişli et al., 2000).

The aim of this study is to determine the morphological characteristics of rose genotypes (Rosa spp.) that could make significant contributions to Yozgat and the national economy.

2. Materials And Methods

This research was conducted in the Yozgat province and its districts between 2015 and 2016. The study aimed to identify types with superior characteristics and involved examining thousands of plants, taking fruit samples from suitable plants and considering each sampled plant a type. The following criteria were primarily considered when determining genotypes: high yield; large fruit size; a high flesh ratio; freedom from diseases and pests; and relatively few thorns. A total of 142 genotypes were identified as a result of the study conducted in 14 districts of Yozgat province. These were compared using a modified weighted grading method, ultimately selecting 49 genotypes. Some morphological characteristics were determined in these genotypes. The crown width of the rosehip genotypes was measured at the widest point of the crown, and the crown height was measured in meters from the ground to the top of the plant (Dölek, 2008). Shoot length and diameter (cm–mm), the length of any three shoots on the shrubs was measured with a tape measure, and their diameter was determined using a vernier caliper accurate to 0.05 mm (Dölek, 2008). Number of shoots per plant (shoots/plant) was determined by counting the shoots present on the shrubs of the rosehip varieties (Dölek, 2008).

The number of fruit spurs per shoot was determined by counting the fruit spurs on three randomly selected shoots and calculating the average. The number of fruits on the clusters of fruit spurs in the selected genotypes was determined by counting the fruits. Leaf chlorophyll content readings were measured using a Konica Minolta SPAD-502 Plus Chlorophyll Meter. Leaf anthocyanin content was determined using an Opti Science ACM-200 Plus Anthocyanin Meter. Leaf area was determined using the ADC Bio Scientific Area Meter AM300. The number of thorns in the first, second, and third 20-centimeter sections starting from the tip of the shoot was counted. The total number of thorns on the shoot was determined, and reference values were established by dividing the shoot length by the number of thorns (Table 1). In the study, statistical analyses were performed using the Duncan multiple comparison test in the SPSS software package.

Table 1. Thorniness scale

Scale No	Number of Thorns (Per 20 cm section)	Thorniness	Thorn spacing on the shoot (cm)
1	0-5.0 adet	Thornless	9,1 <
2	5.1-10.0	Slightly thorny	6,1-9,0
3	10.1-15.0	Moderately thorny	3,1-6,0
4	15.1 ≤	Very thorny	3,0 >

3. Results And Discussions

Plant genetic resources are threatened with depletion or even extinction in their regions due to environmental and other pressures. Their conservation is essential to secure the future of plant production. Research conducted in our country and various parts of the world shows that plant genetic material is rapidly disappearing. In our study, out of 49 genotypes from which we collected fruit samples in September, when we went to take morphological measurements in December, we found that 4 of these genotypes had been destroyed due to reasons such as stubble burning or road construction.

Table 2 presents data on crown width and height, shoot length and diameter, number of shoots per plant, number of fruit twigs per shoot, and number of fruits per cluster for each genotype. Among the selected genotypes, crown width was determined to be at least 152 cm (ÇYR03) and at most 738 cm (BGZ-03), while crown height ranged from at least 142 cm (AYD

07) to at most 480 cm (KDŞ 02). Shoot length ranged from at least 109.00 cm (SRK 17) to at most 272.67 cm (SRG-17); shoot diameter ranged from at least 7.00 mm (BGZ-07) to at most 23.67 mm (MRK-21). The number of shoots per plant was determined to be at least 8 shoots (KDŞ 05, MRK 30) and at most 21 shoots (BGZ 11, MRK 19). The number of fruit twigs per shoot was lowest in SRK 13 (3 units) and highest in AYD 07 (27 units). The selected types showed the lowest number of fruits per cluster in SRK 13 (1 fruit/beam) and the highest in BGZ 04 (6 fruits/beam).

Table 2. Morphological characteristics of selected types

No	Genotype	Crown width (cm)	Crown height (cm)	Shoot Height (cm)	Shoot Diameter (mm)	Number of shoots (pieces)	Number of fruit twigs per shoot (pieces)	Number of fruits per beam (pieces/beam)
1	AKD-02*	-	-	-	-	-	-	-
2	AKD-10	320	230	**233.00 a-c**	**19.00 a-e**	16	9.67 j-p	1.67 f-h
3	AYD-01	273	214	174.33 d-i	**18.00 a-f**	12	12.33 h-n	2.00 e-h
4	AYD-05	470	270	184.00 c-i	13.33 c-i	13	8.67 l-p	2.67 c-g
5	AYD-07	216	**142**	117.67 j-k	12.00 d-i	14	**26.67 a**	1.33 gh
6	AYD-09	310	289	213.33 b-f	13.00 c-i	16	20.00 b	2.33 d-h
7	BGZ-03	**738**	276	162.67 e-j	12.00 d-i	13	10.33 i-p	3.67 b-d
8	BGZ-04	440	246	165.33 e-j	14.33 b-i	14	11.00 i-o	**5.67 a**
9	BGZ-07	498	257	157.33 f-k	**7.00 i**	12	11.33 h-o	4.00 bc
10	BGZ-10	726	251	180.67 c-i	**18.67 a-e**	19	12.67 h-m	2.33 d-h
11	BGZ-11	490	232	173.67 d-j	14.67 b-i	**21**	10.33 i-p	2.67 c-g
12	ÇKR-06	342	289	190.33 b-h	13.33 c-i	17	13.67 e-k	1.67 f-h
13	ÇKR-08	288	215	173.67 d-j	**17.33 a-g**	13	12.67 h-m	2.67 c-g
14	ÇKR-09	268	269	**227.00 a-d**	14.33 b-i	13	9.67 j-p	1.67 f-h
15	ÇYR-02	310	225	200.00 b-h	14.33 b-i	17	13.33 f-k	3.00 c-f
16	ÇYR-03	**152**	340	190.33 b-h	14.67 b-i	12	8.33 m-p	3.33 b-e
17	KDŞ-02	327	**480**	215.67 b-e	15.67 b-h	16	9.33 k-p	2.67 c-g

18	KDŞ-05	217	162	131.33 i-k	9.67 g-i	**8**	8.00 n-p	1.67 f-h
19	KDŞ-07	327	320	179.00 c-i	11.33 e-i	9	7.67 op	2.67 c-g
20	MRK-05	270	220	171.67 d-j	14.33 b-i	13	14.33 c-i	**5.33 a**
21	MRK-06*	-	-	-	-	-	-	-
22	MRK-08*	-	-	-	-	-	-	-
23	MRK-10	372	227	191.33 b-h	14.33 b-i	16	14.00 d-j	2.00 e-h
24	MRK-13	320	248	197.00 b-h	**17.00 a-g**	19	10.67 i-p	2.33 d-h
25	MRK-15	271	275	184.33 c-i	**20.67 a-c**	18	14.00 d-j	2.00 e-h
26	MRK-19	362	221	182.67 c-i	12.00 d-i	**21**	10.67 i-p	2.33 d-h
27	MRK-20	304	223	**224.67 a-d**	**16.33 a-h**	12	17.00 b-g	2.00 e-h
28	MRK-21	427	270	**243.67 ab**	**23.67 a**	17	9.33 k-p	2.00 e-h
29	MRK-27	272	204	166.33 e-j	12.00 d-i	11	11.33 h-o	1.67 f-h
30	MRK-28	218	180	173.00 d-j	14.67 b-i	10	17.67 b-e	3.67 b-f
31	MRK-29	530	260	170.33 d-j	**16.33 a-h**	12	17.67 b-e	3.67 b-d
32	MRK-30	416	256	164.00 e-j	13.00 c-i	**8**	13.00 g-l	3.00 c-f
33	SRG-03	380	250	202.00 b-h	15.67 b-h	13	10.33 i-p	1.67 f-h
34	SRG-05	290	240	170.33 d-j	**20.67 a-c**	12	9.67 j-p	1.67 f-h
35	SRG-08	322	282	171.67 d-j	**18.00 a-f**	17	17.33 b-f	3.00 c-f
36	SRG-13	380	272	200.67 b-h	**21.67 ab**	12	9.67 j-p	2.33 d-h
37	SRG-14	212	220	184.33 c-i	12.67 c-i	18	14.33 c-i	1.33 gh
38	SRG-16	160	163	156.00 c-i	11.33 e-i	11	13.33 f-k	1.33 gh
39	SRG-17	550	340	**272.67 a**	**17.00 a-g**	14	8.00 n-p	2.33 d-h
40	SRK-12	175	230	163.33 e-j	9.67 g-i	9	12.33 h-n	2.67 c-g
41	SRK-13	250	300	147.33 h-k	10.33 f-i	13	**2.67 q**	**1.00 h**
42	SRK-17	280	170	**109.00 k**	8.67 h-i	12	13.00 g-l	2.33 d-h
43	SRK-26	450	233	167.33 e-j	**16.33 a-h**	19	13.67 e-k	3.33 b-e
44	SRK-27	500	260	149.67 g-k	15.00 b-i	19	18.00 b-d	2.67 c-g
45	SRK-33	429	250	173.00 d-j	**20.00 a-d**	15	15.33 c-h	3.33 b-e
46	SRY-02	367	243	207.00 b-g	12.67 c-i	13	18.33 bc	**4.67 ab**
47	ŞFT-03*	-	-	-	-	-	-	-

48	YFK-02	454	237	191.00 b-h	11.00 e-i	11	6.67 p	3.00 c-f
49	YRK-06	320	221	165.00 e-j	**17.67 a-g**	11	11.00 i-o	3.67 b-d

* When the areas where the AKD-02, MRK-06, MRK-08 and ŞFT-03 genotypes were found were visited to determine their morphological characteristics, it was observed that the plants had been destroyed due to reasons such as stubble burning or road construction.

Akkuş (2016), in order to examine the natural rosehip (Rosa spp.) population in the Hamur (Ağrı) region and to select superior genotypes, estimated the productivity level of the 71 genotypes he determined as high for 18 genotypes, medium for 29 genotypes, low for 16 genotypes, and very low for 8 genotypes. Azgın (2017) reported that among the 106 genotypes he determined in the Akkuş (Ordu) region, the productivity was high in 28 genotypes, medium in 45 genotypes, low in 31 genotypes, and very low in 2 genotypes. Bozdoğan (2025) made an observational estimate of the yield by looking at the number of fruits in the clusters on the fruit branch and determined that 15 genotypes were very productive, 12 were medium productive, and 2 were low productive.

Leaf chlorophyll content, anthocyanin content, leaf area measurements, and shoot thorniness are given in Table 3. Leaf chlorophyll content (SPAD) values in rosehip genotypes ranged from 29.6 (MRK 13) to 59.6 (AYD 07). Anthocyanin content (ACI) measured in the leaves ranged from a minimum of 4.3 (YFK 02) to a maximum of 16.9 (AYD 07) in our genotypes. Leaf area measurements showed a minimum value of 11.23 cm² (AYD 07) and a maximum value of 70.89 cm² (ÇYR 03). Leaf characteristics are among the parameters used to differentiate genotypes, and differences in results may be observed depending on the plant material used (Balasooriya et al., 2009). In their study, Bozdoğan (2025) obtained the highest leaf area in genotype K-15 with 6.88 cm^2, while the lowest values were obtained from genotypes K-1 with 2.75 cm^2 and K-19 with 2.82 cm^2.

The degree of thorniness in the shoots was determined to be slightly thorny in 11 genotypes, moderately thorny in 33 genotypes, and very thorny in 1 genotype in our study. Şavir (2008) determined that 2 out of 50 rosehip genotypes selected from Erzincan province were thornless, while Yıldız and Çelik (2011) reported that 4 out of 50 genotypes in the Muradiye (Van) region, and Ekincialp and Kazankaya (2012) reported that 4 out of 50 genotypes in the Hakkari region had mild thorniness. Salman-Özen (2013) observed mild thorniness in 34 out of 100 genotypes selected from the Bolu region. Akkuş (2016), in his study with 71 genotypes in the Hamur

(Ağrı) region, identified 4 genotypes as thornless. Azgın (2017) observed that 17 out of 106 genotypes in the Akkuş (Ordu) region had mild thorniness, while reporting that no thornless genotypes were found. Bozdoğan (2025) determined that the thorniness of 29 genotypes was very thorny in 1, moderately thorny in 23 and slightly thorny in 5.

Table 3. Leaf measurement values and shoot thorniness status of selected genotypes

No	Genotypes	Leaf Chlorophyll Content (SPAD)	Leaf Anthocyanin Content (ACI)	Leaf Area (cm^2)	Thorny
1	AKD-10	44.1	8.7	23.12	Moderately thorny
2	AYD-01	36.6	6.9	20.02	Moderately thorny
3	AYD-05	40.8	6.5	17.15	Moderately thorny
4	AYD-07	**59.6**	**16.9**	**11.23**	Moderately thorny
5	AYD-09	43.7	10.1	40.28	Moderately thorny
6	BGZ-03	41.8	7.8	28.53	Slightly thorny
7	BGZ-04	45.8	9.2	22.02	Moderately thorny
8	BGZ-07	41	6.6	33.73	Moderately thorny
9	BGZ-10	44.6	8.4	19.97	Moderately thorny
10	BGZ-11	34.2	6.0	46.46	Moderately thorny
11	ÇKR-06	32.3	5.1	17.14	Moderately thorny
12	ÇKR-08	35	5.1	17.36	Moderately thorny
13	ÇKR-09	30.6	4.7	33.53	Moderately thorny
14	ÇYR-02	33.6	4.8	37.19	Slightly thorny
15	ÇYR-03	51.7	10.6	**70.89**	Moderately thorny
16	KDŞ-02	37.3	6.5	27.69	Slightly thorny
17	KDŞ-05	48.4	9.9	28.84	Moderately thorny
18	KDŞ-07	42.8	7.7	25	Slightly thorny
19	MRK-05	43.8	8.9	17.24	Moderately thorny
20	MRK-13	**29.6**	4.6	25.69	Moderately thorny
21	MRK-15	36.6	6.3	25.1	Moderately thorny
22	MRK-19	37.8	5.9	22.94	Slightly thorny
23	MRK-20	34.5	5.2	42.33	Moderately thorny
24	MRK-21	35.8	6.5	19.84	Moderately thorny
25	MRK-27	35.6	5.7	27.55	Moderately thorny

26	MRK-28	35.7	5.3	11.58	Moderately thorny
27	MRK-29	47.5	10.0	23.55	Slightly thorny
28	MRK-30	36.9	6.7	27.19	Moderately thorny
29	SRG-03	30.3	4.9	19.03	Moderately thorny
30	SRG-05	35.9	6.3	16.69	Moderately thorny
31	SRG-08	34.9	5.5	20.13	Moderately thorny
32	SRG-13	39.3	7.9	27.32	Slightly thorny
33	SRG-14	37.9	6.2	16.51	Slightly thorny
34	SRG-16	40.3	8.3	13.9	Moderately thorny
35	SRG-17	35.6	5.1	24.62	Moderately thorny
36	SRK-12	37.1	5.6	26.29	Moderately thorny
37	SRK-13	51.5	10.8	15.98	Moderately thorny
38	SRK-17	39.1	7.1	34.81	Slightly thorny
39	SRK-26	38.9	6.7	33.09	Moderately thorny
40	SRK-27	33.2	5.1	30.7	Moderately thorny
41	SRK-33	33.7	5.4	33.64	Very thorny
42	SRY-02	35.6	5.9	24.93	Moderately thorny
43	ŞFT-03	46.1	9.2	36.13	Slightly thorny
44	YFK-02	32.7	**4.3**	24.58	Slightly thorny
45	YRK-06	57.9	15.4	28.98	Moderately thorny

5. Conclusion

Survey and selection studies conducted in our country and various regions of the world clearly show that plant genetic resources are gradually decreasing. Factors such as stubble burning, road construction, the effects of global climate change, increasing pressure from diseases and pests, natural disasters, and the expansion of settlements are causing the genetic

diversity of rosehip, like many other fruit species, to be at risk and lost over time. This study provided detailed and comprehensive data on the phenotypic diversity of rosehip populations identified in Yozgat and its districts. It is anticipated that these findings will serve as a significant scientific resource and guide for future studies in this field and/or similar topics.

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ROSEHIP SELECTION IN YOZGAT, TÜRKİYE: FRUIT CHARACTERISTICS

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Abstract

The study aimed to select rosehip varieties with superior characteristics from those growing naturally in Yozgat Province and its districts. Following the preliminary selection, fruit samples were collected from 142 rosehip genotypes identified across the province's 14 districts. Using a modified weighted rating system, 49 genotypes were identified as promising in the first year. In the second year of the selection process, the pomological characteristics of the genotypes chosen in the previous year were examined. Certain characteristics were identified as quality criteria for rose hips. The genotypes examined had an average fruit width ranging from 10.21 mm (66 MRK 20) to 15.78 mm (66 ÇYR 03) and an average fruit length ranging from 16.67 mm (66 AYD 07) to 29.64 mm (66 YRK 06). The average number of seeds per fruit ranged from 2.23 (66 ÇYR 03) to 41.07 (66 MRK 29), and the average seed weight ranged from 0.006 g (66 AYD 07) to 0.072 g (66 ÇYR 03). Sensory analysis of the selected rosehip genotypes revealed that 19 had a good taste, 22 had a moderate taste and eight had a poor taste. The fruit shape of the selected rosehip types was observed to be: conical (12); truncated conical (12); elliptical (5); long elliptical (1); oval (2); and cylindrical (17). SRK 13 had the lowest fruit shape index value (1.26), while YRK 06 had the highest (2.30). Observations revealed that one type (ÇYR-03) had external pubescence, while the remaining 48 types did not. Of the examined genotypes, it was observed that eight had high internal pubescence, 39 had moderate internal pubescence and two had low internal pubescence. The research findings reveal that rose hips growing naturally in the region exhibit variations in certain physical and chemical properties. Furthermore, the study has highlighted the presence of a dense rose hip population in the region.

Keywords: Rosehip, Yozgat, selection, fruit characteristics

YOZGAT/ TÜRKİYE'DE KUŞBURNU SELEKSİYONU: MEYVE ÖZELLİKLERİ

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Özet

Çalışmada Yozgat ili ve ilçelerinde doğal olarak yetişen kuşburnularda üstün özelliklere sahip olanlarının seçilmesi amaçlanmıştır. Ön seleksiyon sonucunda 14 ilçeden tespit edilen toplam 142 kuşburnu genotipinde yapılan değiştirilmiş tartılı derecelendirme sonucunda, birinci yıl 49 tip ümitvar olarak bulunmuştur. Seleksiyonun ikinci yılında, birinci yıl seçilen genotiplerin pomolojik özellikleri incelenmiştir. Kuşburnularda kalite kriteri olarak ele alınan bazı özellikler belirlenmiştir. İncelenen genotiplerin ortalama meyve eni 10.21 mm (66 MRK 20) ile 15.78 mm (66 ÇYR 03), meyve boyu 16.67 mm (66 AYD 07) ile 29.64 mm (66 YRK 06), çekirdek sayısı 2.23 adet/meyve (66 ÇYR 03) ile 41.07 adet/meyve (66 MRK 29), çekirdek ağırlığı 0.006 g (66 AYD 07) ile 0.072 g (66 ÇYR 03) arasında tespit edilmiştir. Selekte edilen kuşburnu genotiplerinde yapılan duyusal analizler sonucu 19 tanesinin iyi, 22 tanesinin orta, 8 tanesinin ise kötü tada sahip olduğu belirlenmiştir. Meyve şekilleri ise 12 tanesinin konik, 12 tanesinin kesik konik, 5 tanesinin eliptik, 1 tanesinin uzun eliptik, 2 tanesinin oval, 17 tanesinin ise silindirik olduğu gözlemlenmiştir. Meyve şekil indeksi değeri en düşük 66 SRK 13 (1.26) ve en yüksek 66 YRK 06 (2.30) olduğu tespit edilmiştir. Kuşburnu tiplerinde gözlemler sonucu 1 tipte (ÇYR-03) dış tüylülük olduğu, geri kalan 48 tipte ise dış tüylülük olmadığı gözlemlenmiştir. İncelenen kuşburnu genotiplerinin 8 tanesinin çok, 39 tanesinin orta, 2 tanesinin ise az iç tüylülüğe sahip olduğu belirlenmiştir. Araştırma sonuçları bölgede doğal olarak yetişen kuşburnuların bazı fiziksel ve kimyasal özellikler bakımından varyasyon gösterdiğini ortaya koymaktadır. Ayrıca çalışma, bölgede yoğun bir kuşburnu popülasyonun varlığını da öne çıkarmıştır.

Anahtar Kelimeler: Kuşburnu, Yozgat, seleksiyon, meyve özellikler

1. Introduction

The genus Rosa, which belongs to the Rosaceae family and is represented by 24 species in Turkey, grows wild in many regions and is also cultivated in some. One of these species, Rosa canina L., has various common names, including rosehip, dog rose, wild rose, pig radish, dog rose, rosehip and rose apple (Davis, 1972; Baytop, 1999).

Anatolia lies at the intersection of two of the world's most important gene centres. Many species of fruit that thrive in temperate climates (such as apricots, apples, pears, quinces, walnuts, hazelnuts, chestnuts and almonds) and their wild forms originate in Anatolia. In terms of cultivated and edible wild fruit species, Anatolia is like a collection garden. Most of the edible wild fruit species found in our country are used by our people for various purposes. One of the most notable of these is the rosehip, which has a long history of use dating back to ancient times (Ercisli & Esitken, 2004).

Rosehip is used as a valuable raw material in the food and pharmaceutical industries in many European countries, particularly Germany, as well as in Russia, the Turkic Republics, Switzerland and Finland (Yamankaradeniz, 1983). In these countries, rosehip fruits are used to make fruit gels, baby food, fruit juice, marmalade and tea. As well as enriching other fruit and vegetable juices with vitamins, rosehip is also widely used as an additive in the pastry and confectionery industry. Its importance in Turkey has increased, especially in recent years. In fruit processing factories and businesses, rosehip is used to make fruit juice, marmalade, pulp and tea bags. Despite having a long tradition of fruit cultivation, our country has very few varieties of some types of fruit, such as rosehip. These include the YILDIZ variety, which was registered in 2012, the Gerçekcioğlu variety, which was registered in 2015, and the Ay variety, which was registered in 2022 (Anonymous 2026).

This study is important in determining superior genotypes of rosehip, which has been known and consumed worldwide for many years, and whose consumption is increasing in our country. These genotypes were identified in the natural growing environment of Yozgat province, and will serve as a source for later studies.

2. Materials And Methods

In the preliminary selection study, 142 genotypes were selected from surveys conducted in the districts of Yozgat, identified as high-yielding, with large fruits, a high fruit-to-pulp ratio,

free from diseases and pests, and having few thorns (Dölek, 2008). Fruit samples were collected from the genotypes identified in the survey during September and October, subjected to a weighted evaluation, and 49 of them were identified as promising types. In these fruits, fruit length and width (mm) of a fruit randomly selected from each type were measured using a digital caliper accurate to 0.01 mm (Ercişli, 1996; Çelik, 2007). Number of seeds (per fruit) determined by removing the seeds from 30 randomly selected fruits and counting them separately for each fruit. Seed weight (g) was determined by weighing the seeds removed from 30 randomly selected fruits of each type separately on a 0.01 g precision balance and dividing the total by the number of seeds. Taste Test (Degustation) were classified as good, average or poor based on sensory analyses of the rosehip fruits (Dölek, 2008). Fruit shapes of the rosehip genotypes were determined according to Ercişli (1996). Fruit shape index (length/width) was determined by dividing the average fruit length by the average fruit width of 30 randomly selected fruits (Ercişli, 1996).

In the study, statistical analyses were performed using the Duncan multiple comparison test in the SPSS software package.

3. Results And Discussions

The pomological characteristics of the selected rosehip genotypes are presented in Table 1 and Table 2. Among the selected rosehip genotypes, the genotype with the smallest fruit width was identified as MRK 20 (10.21) and the genotype with the largest fruit width as ÇYR 03 (15.78). Among the genotypes, the genotype with the smallest fruit length was identified as AYD 07 (16.67) and the genotype with the largest fruit length as YRK 06 (29.64). Among the selected rosehip types, the type with the fewest seeds was identified as ÇYR 03 (2.23 seeds/fruit) and the type with the most seeds was identified as MRK 29 (41.07 seeds/fruit). Among the rosehip types, the type with the lowest seed weight was AYD 07 (0.006 g), and the type with the highest seed weight was ÇYR 03 (0.072 g). Sensory analyses conducted on the selected rosehip genotypes revealed that 19 had a good aroma, 22 had a moderate aroma, and 8 had a poor aroma (Table 1).

Of the selected rosehip types, 12 were observed to be conical, 12 were truncated conical, 5 were elliptical, 1 was long elliptical, 2 were oval, and 17 were cylindrical. Among the examined rosehip types, the type with the lowest fruit shape index value was SRK 13 (1.26) and the type with the highest value was YRK 06 (2.30). Observations revealed that 1 type (ÇYR-03) had

external pubescence, while the remaining 48 types did not. It was observed that 8 of the examined rosehip genotypes had a lot of internal pubescence, 39 had a moderate amount, and 2 had a little internal pubescence (Table 2).

In their study conducted in Tokat and the surrounding area, Kara and Gerçekçioğlu (1992) found that the fruit length was 25.78 mm, the fruit width was 15.93 mm, and the number of seeds was 29. Kocamaz and Karakoç (1994) reported that fruit lengths ranged from 15.7 to 25.5 mm and fruit widths from 12.3 to 19.9 mm. Balta and Çam (1996), in their study conducted in the Gevaş and Ahlat regions, found that fruit width ranged from 12.26–17.73 mm and fruit length from 18.85–29.89 mm. Şen and Güneş (1996), in a study conducted in the Tokat region, recorded that fruit widths ranged from 12.26–18.71 mm, fruit lengths from 18.34–36.46 mm, and the number of seeds from 14.7–46.20]. Kazankaya et al. (1999) reported that the seed weights of wild rose hips growing naturally in the Van region ranged from 0.01 to 0.90 g. Mısırlı et al. (1999), in their study conducted in İzmir-Kemalpaşa, found that the fruit width was 12.24–15.07 mm, the number of seeds was 18.25–32.82, and the seed weight was 0.314–0.863 g. Türkben et al. (1999) determined that the fruit lengths of wild rose hips growing naturally in the Bursa region ranged from 15.33–21.83 mm, fruit widths from 10.27–14.53 mm, and seed counts from 11.00–35.33. Kazankaya et al. (2001) reported in their study conducted in the Adilcevaz region that fruit length ranged from 15.41 to 27.76 mm, fruit width from 9.14 to 18.48 mm, the number of seeds from 14 to 52, and total seed weight from 0.21 to 1.66 g. Kazankaya et al. (2002), in a study on naturally occurring rosehip fruits in the Gevaş and Edremit regions, found that fruit widths ranged from 10.41–15.53 mm, fruit lengths from 10.40–25.10 mm, seed weights ranging from 0.013 to 0.051 g, and seed counts ranging from 15 to 32. Türkoğlu and Muradoğlu (2003), in their study conducted in the Tatvan region, reported that fruit widths ranged from 9.65–18.36 mm, fruit lengths from 8.20–16.67 mm, and seed counts from 10–45. Kazankaya et al. (2005), in their study conducted in the Hakkâri, Bitlis and Van regions, reported that fruit lengths ranged from 1.23–4.43 cm, fruit widths from 1.03–2.66 cm, and seed counts from 18.6–41.6. Kızılcı (2005) determined that fruit lengths ranged from 13.002–32.968 mm, fruit widths from 13.778–20.882 mm, and seed counts from 5.94–35.089. Doğan and Kazankaya (2006) reported that the fruit lengths of R. canina, R. foetida, R. iberica, R. dumalis, R. pisiformis and R. pimpinellifolia, which grow naturally in the Van region, ranged from 18.40 to 27.40 mm. Şavir (2008), in his study aimed at selecting genotypes with superior characteristics from rosehips growing naturally in 4 villages and towns at the foot of Munzur Mountain in Erzincan Center, examined 50 rosehip types and identified 15

promising types according to selection criteria. The aroma status of these types was determined as follows: 2 very sour, 18 sour, 28 tart, and 2 sweet.

Table 1. Values for certain physical characteristics of the selected genotypes

No	Genotype	Fruit Width (mm)	Fruit Length (mm)	Number of Seeds (Pieces)	Seed Weight (g)	Sensory Analysis
1	AKD-02	13,57 b-f	20,20 m-q	28,27 h-l	0,019	Poor
2	AKD-10	13,06 b-l	20,33 m-p	35,30 cd	0,023	Moderate
3	AYD-01	12,07 e-p	23,03 f-h	20,73 qr	0,024	Good
4	AYD-05	13,42 b-g	20,04 n-q	25,43 k-o	0,038	Poor
5	AYD-07	10,40 op	**16,67 w**	14,77 s	**0,006**	Poor
6	AYD-09	**14,31 a-d**	24,05 d-f	**39,43 ab**	0,017	Good
7	BGZ-03	12,62 b-n	20,92 k-n	31,47 d-i	0,021	Good
8	BGZ-04	12,67 b-n	20,24 m-q	33,20 c-f	0,029	Poor
9	BGZ-07	11,54 g-p	23,07 f-g	27,40 i-m	0,026	Good
10	BGZ-10	12,30 d-o	18,77 r-u	29,20 f-k	0,024	Good
11	BGZ-11	13,77 b-e	24,74 d	24,60 l-q	0,026	Good
12	ÇKR-06	11,10 k-p	19,58 o-r	21,80 o-r	0,016	Good
13	ÇKR-08	11,25 i-p	19,30 p-s	26,03 j-n	0,024	Moderate
14	ÇKR-09	**14,41 a-c**	21,48 j-l	28,13 h-l	0,030	Moderate
15	ÇYR-02	13,27 b-i	22,69 g-i	27,93 h-l	0,024	Good
16	ÇYR-03	**15,78 a**	27,37 c	2,23 t	**0,072**	Good
17	KDŞ-02	13,04 b-l	23,38 e-g	20,57 q-r	0,027	Moderate
18	KDŞ-05	11,18 j-p	17,31 vw	23,67 m-r	0,017	Moderate
19	KDŞ-07	12,57 b-n	18,27 s-v	22,80 n-r	0,020	Moderate
20	MRK-05	11,34 h-p	20,68 l-o	24,30 l-r	0,028	Moderate
21	MRK-06	13,29 b-h	23,04 f-h	32,47 d-g	0,027	Moderate
22	MRK-08	11,55 g-p	18,76 r-u	21,17 p-r	0,023	Moderate
23	MRK-10	12,40 c-n	22,74 g-i	26,73 j-n	0,019	Moderate
24	MRK-13	13,12 b-k	21,82 i-k	33,67 c-e	0,025	Moderate
25	MRK-15	13,73 b-f	20,47 l-o	35,37 cd	0,025	Moderate
26	MRK-19	**14,28 a-d**	21,27 j-m	31,83 d-h	0,022	Moderate
27	MRK-20	**10,21 p**	19,26 p-s	13,80 s	0,022	Good
28	MRK-21	13,03 b-l	19,98 n-q	24,67 l-q	0,027	Moderate

29	MRK-27	12,62 b-n	21,92 h-k	21,00 p-r	0,026	Good
30	MRK-28	13,04 b-l	23,95 d-f	**40,80 a**	0,020	Poor
31	MRK-29	**14,58 ab**	20,93 k-n	**41,07 a**	0,023	Good
32	MRK-30	13,17 b-j	22,25 g-j	32,40 d-g	0,028	Moderate
33	SRG-03	11,00 m-p	18,63 r-u	26,77 j-n	0,016	Poor
34	SRG-05	12,48 c-n	22,59 g-i	29,03 g-k	0,022	Moderate
35	SRG-08	13,95 a-e	18,00 t-v	25,07 k-p	0,031	Poor
36	SRG-13	11,71 f-p	17,18 vw	25,97 j-n	0,019	Good
37	SRG-14	12,11 e-p	17,86 uv	27,67 i-m	0,018	Moderate
38	SRG-16	12,58 b-n	19,11 q-t	31,90 d-h	0,017	Moderate
39	SRG-17	**14,23 a-d**	28,42 b	27,90 h-m	0,032	Good
40	SRK-12	10,92 n-p	**16,75 w**	22,63 n-r	0,015	Good
41	SRK-13	**14,25 a-d**	17,92 uv	37,00 bc	0,017	Good
42	SRK-17	11,06 l-p	21,80 i-k	20,27 r	0,024	Good
43	SRK-26	11,07 l-p	19,71 o-r	26,57 j-n	0,019	Moderate
44	SRK-27	11,39 h-p	20,02 n-q	26,00 j-n	0,023	Moderate
45	SRK-33	13,01 b-m	17,92 uv	29,87 e-j	0,021	Good
46	SRY-02	12,45 c-n	18,08 t-v	25,47 k-o	0,019	Poor
47	ŞFT-03	**13,95 a-e**	24,24 de	36,67 bc	0,029	Moderate
48	YFK-02	11,48 g-p	17,74 u-w	29,17 f-k	0,022	Good
49	YRK-06	12,90 b-n	**29,64 a**	31,53 d-i	0,027	Moderate

Yıldız ve Çelik (2011), in his study aimed at selecting promising genotypes from rosehip populations growing naturally in the Muradiye region of Van, evaluated 80 rosehip genotypes. As a result of his evaluations, he reduced the number of genotypes to 50. In these genotypes, he determined the fruit length to be between 20.68-27.34 mm and the fruit width to be between 12.97-15.74 mm.

Table 2. Data on fruit shape, shape index, and internal and external pubescence characteristics of selected genotypes

No	Genotype	Fruit shape	Fruit shape index	Fruit External pubescence	Fruit internal pubescence
1	AKD-02	truncated conical	1,49	not available	high
2	AKD-10	conical	1,56	not available	high
3	AYD-01	elliptical	1,91	not available	high
4	AYD-05	truncated conical	1,49	not available	moderate
5	AYD-07	conical	1,60	not available	high
6	AYD-09	conical	1,68	not available	high
7	BGZ-03	conical	1,66	not available	moderate
8	BGZ-04	conical	1,60	not available	moderate
9	BGZ-07	elliptical	2,00	not available	moderate
10	BGZ-10	conical	1,53	not available	moderate
11	BGZ-11	cylindrical	1,80	not available	moderate
12	ÇKR-06	cylindrical	1,76	not available	moderate
13	ÇKR-08	cylindrical	1,72	not available	moderate
14	ÇKR-09	truncated conical	1,48	not available	moderate
15	ÇYR-02	cylindrical	1,71	not available	low
16	ÇYR-03	cylindrical	1,73	available	low
17	KDŞ-02	cylindrical	1,79	not available	moderate
18	KDŞ-05	conical	1,55	not available	moderate
19	KDŞ-07	truncated conical	1,45	not available	moderate
20	MRK-05	cylindrical	1,82	not available	moderate
21	MRK-06	cylindrical	1,73	not available	moderate
22	MRK-08	conical	1,62	not available	high
23	MRK-10	cylindrical	1,83	not available	moderate
24	MRK-13	conical	1,66	not available	moderate
25	MRK-15	truncated conical	1,49	not available	moderate
26	MRK-19	truncated conical	1,49	not available	moderate
27	MRK-20	elliptical	1,89	not available	moderate
28	MRK-21	conical	1,53	not available	moderate
29	MRK-27	cylindrical	1,74	not available	moderate
30	MRK-28	cylindrical	1,84	not available	moderate
31	MRK-29	truncated conical	1,44	not available	moderate
32	MRK-30	cylindrical	1,69	not available	moderate
33	SRG-03	cylindrical	1,69	not available	moderate
34	SRG-05	cylindrical	1,81	not available	moderate
35	SRG-08	oval	1,29	not available	moderate
36	SRG-13	truncated conical	1,47	not available	moderate
37	SRG-14	truncated conical	1,48	not available	moderate
38	SRG-16	truncated conical	1,52	not available	moderate
39	SRG-17	elliptical	2,00	not available	moderate
40	SRK-12	conical	1,53	not available	high
41	SRK-13	oval	**1,26**	not available	moderate
42	SRK-17	elliptical	1,97	not available	moderate
43	SRK-26	cylindrical	1,78	not available	moderate
44	SRK-27	cylindrical	1,76	not available	high
45	SRK-33	truncated conical	1,38	not available	moderate
46	SRY-02	truncated conical	1,45	not available	moderate
47	ŞFT-03	cylindrical	1,74	not available	moderate
48	YFK-02	conical	1,55	not available	moderate
49	YRK-06	long elliptical	**2,30**	not available	moderate

Encu (2015), Van province; In the study, which aimed to examine the pomological and some biochemical characteristics of the Rosa canina species from rosehips selected from 6 different regions, namely Gevaş, Çatak, Erciş districts of Hakkâri province; Şemdinli and Yüksekova districts of Şırnak province; and Uludere district, the fruit width was determined as 10.78-14.63mm and the fruit length as 15.49-25.29mm. Akkuş (2016), in his study to examine the natural rosehip population of the Hamur (Ağrı) region and to morphologically identify the superior genotypes (Rosa spp.), examined 71 genotypes of Rosadumalis, Rosadumalis var. Boissieri, Rosa canina, Rosa pisiformis, Rosa villosa and Rosa spp. species within the natural population according to rosehip selection criteria, and evaluated 24 genotypes as promising. In the 71 genotypes examined, the fruit width was recorded as 12.06-19.49 mm, the fruit length as 18.09-28.85 mm, the seed weight as 0.36-1.75 g, the number of seeds as 14-41, and the fruit shape index as 1.13-2.03.

5. Conclusion

Due to its geographical location at the intersection of the Near East and Mediterranean gene centers, our country is one of the unique and important countries in the world in terms of plant genetic resources and genetic diversity. This diversity includes wild relatives of local cultivated plant species. Furthermore, the fact that it is an area where fruit species grow naturally means that it should not be overlooked in terms of plant genetic resources. Plant genetic resources are facing the threat of decline or even extinction in their regions due to environmental and other pressures. Their protection is essential for securing the future of plant production. Surveys conducted in our country and in various regions of the world show that plant genetic material is rapidly disappearing. Factors such as global climate change, various diseases and pests, natural disasters, and the development of settlements are causing the loss of genetic resources for rosehips, as is the case with many fruit species. Our results have provided quite detailed data on genetic variation in the rosehip population in the region where morphological characteristics were determined. It can be said that the results and findings we obtained can be used to shed light on possible future studies on this and similar topics.

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INCLUSIVE EDUCATION IN THE AGE OF TRANSFORMATION: NATURE- AND SCIENCE-BASED APPROACHES FOR INDIVIDUALS WITH SPECIAL NEEDS

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Abstract

This study presents an innovative educational model aimed at developing 21st-century skills in individuals with special needs through nature- and science-based education. The model targets middle school students with mild intellectual disabilities in Istanbul, along with their teachers and parents, and seeks to enhance individuals' scientific curiosity, critical thinking, and problem-solving skills.

The findings obtained at the end of the study indicate that nature-based education has positive effects on individuals' scientific skills, environmental awareness, and social interaction. In this context, the study demonstrates significant potential for increasing environmental awareness and fostering 21st-century skills among individuals with special needs. The methodology of the project includes activities such as direct nature observation, field trips, open- and closed-ended experiments, and creative drama. These activities are designed to support the development of students' cognitive, social, and motor skills. Through hands-on learning experiences, students have the opportunity to explore ecosystems and conduct scientific observations, while teachers gain knowledge and skills to make their educational environments more inclusive by experiencing methods applicable to special education. Parents are also supported through online seminars that provide guidance on how to contribute to their children's education.

The main findings of the study show that nature- and science-based educational practices are effective in increasing learning motivation and enhancing environmental sensitivity among individuals with special needs. As a result, the study recommends the wider implementation of nature-based education in special education. It has been observed that nature-based activities make significant contributions to the cognitive and social development of students, particularly those in inclusive education settings. Expanding this project to reach broader audiences is recommended in order to strengthen the connection of individuals with special needs with society and to increase their interaction with nature.

Keywords: Inclusive Education, Nature-Based Learning, Science Education, Individuals with Special Needs, 21st Century Skills

DÖNÜŞÜM ÇAĞINDA KAPSAYICI EĞİTİM: ÖZEL GEREKSİNİMLİ BİREYLER İÇİN DOĞA VE BİLİM TEMELLİ YAKLAŞIMLAR

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Özet

Bu çalışma, doğa ve bilim temelli eğitim yoluyla özel gereksinimli bireylerde 21. yüzyıl becerilerinin kazandırılmasını amaçlayan yenilikçi bir eğitim modelini tanıtmaktadır. İstanbul'da hafif düzeyde zihinsel yetersizliği olan ortaokul öğrencileri, öğretmenleri ve ebeveynlerini hedef alan bu eğitim modeli, bireylerin bilimsel merak, eleştirel düşünme ve problem çözme yetkinliklerini geliştirmeyi hedeflemektedir.

Çalışma sonunda ende edilen bulgular, doğa temelli eğitimin bireylerde bilimsel beceriler, çevre bilinci ve sosyal etkileşim alanlarında olumlu etkiler yarattığını göstermektedir. Bu bağlamda, çalışmanın özel gereksinimli bireylerde çevre bilincini artırma ve 21. yüzyıl becerilerini kazandırma potansiyeli taşımaktadır. Projenin yönteminde, doğrudan doğa gözlemi, saha gezileri, açık-kapalı uçlu deneyler ve yaratıcı drama gibi etkinlikler yer almaktadır. Bu etkinlikler, öğrencilerin bilişsel, sosyal ve motor becerilerinin gelişimini destekleyecek şekilde tasarlanmıştır. Uygulamalı eğitimlerle öğrenciler, doğadaki ekosistemleri tanıma ve bilimsel gözlem yapma fırsatı bulurken, öğretmenler ise özel eğitimde kullanılacak yöntemleri deneyimleyerek eğitim ortamlarını daha kapsayıcı hale getirme bilgi ve becerisi kazanmaktadır. Ebeveynlere de çevrimiçi seminerler aracılığıyla çocuklarının eğitimine nasıl destek olabilecekleri aktarılmaktadır.

Çalışma sonunda elde edilen temel bulguları, doğa ve bilim temelli eğitimlerin özel gereksinimli bireylerin öğrenme motivasyonunu artırmada ve onların çevreye duyarlılığını geliştirmede etkili olduğunu göstermektedir. Çalışmanın sonucunda, doğa temelli eğitimin özel eğitimde yaygınlaştırılması önerilmektedir. Özellikle kaynaştırma eğitimi alan öğrenciler için doğa temelli faaliyetlerin bireylerin bilişsel ve sosyal gelişimlerine büyük katkı sağladığı görülmüştür. Bu projenin geniş kitlelere ulaşması, özel gereksinimli bireylerin toplumla daha güçlü bir bağ kurması ve doğa ile etkileşimlerini artırması için önerilmektedir.

Anahtar Kelimeler: Kapsayıcı Eğitim, Doğa Temelli Öğrenme, Bilim Eğitimi, Özel Gereksinimli Bireyler, 21. Yüzyıl Becerileri

1.INTRODUCTİON

The integration of individuals with special needs into society and the enhancement of their interaction with nature are crucial components of the principles of equality and inclusivity in education (Doğaroğlu & Dümenci, 2015). Nature- and science-based education possesses the potential to enable individuals to explore their natural environment, develop critical thinking skills, and acquire problem-solving abilities (Gözün & Yıkmış, 2004). It is observed that nature-based education particularly contributes to the development of cognitive and social skills in individuals with special needs by sparking curiosity and fostering a desire for observation and research (Yılmaz, 2013; Vural & Yıkmış, 2008).

In this context, previous studies on nature education demonstrate that, besides increasing environmental awareness, such practices have positive effects on the social integration of individuals with special needs (Sucuoğlu, 2006; Villa & Thousand, 1995). The research by Villa and Thousand (1995) also indicates that inclusive education encourages individuals with disabilities to exist independently and securely within society. Similarly, Gözün and Yıkmış (2004) emphasize that inclusive education supports the adaptation processes of individuals with special needs by focusing on their capabilities. These studies reveal that nature- and science-based activities contribute to individuals with special needs expressing themselves, developing an interest in nature, and participating more actively in social life (Chubon, 1982; Horne, 1985).

Purpose and Hypothesis of the Research

The primary objective of this study is to examine the impact of nature- and science-based education on students with special needs. Furthermore, it aims to provide a more inclusive environment in special education by improving teachers' skills in utilizing nature-based activities and involving parents in this process. As a hypothesis, it is posited that nature-based activities will positively enhance the cognitive, social, and motor skills of students with special needs.

Research Questions

- How does nature-based education contribute to the cognitive and social development of students with special needs?
- How do teachers' knowledge and skills regarding nature-based education methods change?

- What is the impact of parental involvement in their children's nature- and science-based education on the children's environmental awareness?

2.METHOD

This research was conducted using a mixed-methods design to examine the effects of nature- and science-based education on students with special needs. The study was carried out with a sample group consisting of students with mild intellectual disabilities attending middle schools in Istanbul, along with their teachers and parents. Data were collected and analyzed through various data sources.

Participants

The participants of the study consist of 10 inclusive students with special needs, 15 teachers (5 special education teachers and 10 teachers from other disciplines), and 20 parents. Participants were selected based on voluntary application and specific criteria. The special education status of the students was determined by reports from the Counseling and Research Center (RAM).

Data Collection Tools

Due to the alignment of the project with TÜBİTAK 4008 criteria, the fact that it is not a formal research project, and the inability to establish experimental and control groups, the study was designed as a one-group pre-test/post-test quasi-experimental model without a control group.

Pre-survey studies will be conducted during the project implementation process, followed by post-survey studies at the conclusion of the activities. The questions were prepared in a Yes/No format.

The pre-survey is a measurement tool consisting of items with two options (Yes-No). This study will measure the participants' readiness and prior knowledge regarding nature. The post-survey is also a measurement tool consisting of items with two options (Yes-No). Through these surveys, changes in students' perspectives toward nature and their knowledge-comprehension levels will be evaluated. The items were prepared by experts in the field, taking into account the planned activities and scientific studies.

3.FINDINGS

In this study, the impact of science- and nature-based educational practices within the "Journey to Nature Awareness" project on individuals with special needs was examined. The improvements observed and the data obtained at the conclusion of the study are presented below.

Table 1: *Developments Obtained at the Conclusion of the Study*

Research Question	**Anticipated Findings**
How does nature-based education contribute to the cognitive and social development of students with special needs?	- Enhancement in cognitive skills (e.g., attention, memory). (Activities such as *Floating Candle*, *How Many Liters of Water Do We Wear?*, *Orienteering in Nature*...) - Improvement in social interactions (e.g., communication, collaboration).
How do teachers' knowledge and skills regarding nature-based education methods change?	- Increase in the level of knowledge regarding nature-based educational practices. - More frequent integration of nature-based methods into classroom activities.
What is the impact of parental involvement in nature- and science-based education on their children's environmental awareness?	- Visible increase in children's environmental awareness and ecological sensitivity. - More active participation of parents in nature-based activities with their children.

Furthermore, a table illustrating the positive effects of nature on students' individual learning experiences is as follows:

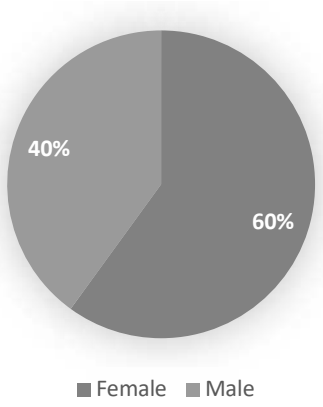
Table 2: *Data on the Positive Effects of Nature on Students' Individual Learning Experiences*

Impacts	**Observed Development**
Cognitive Development	- Increase in attention span - Improvement in problem-solving skills
Social Development	- Increase in participation in group work and collaboration skills - Strengthening of self-expression skills in social interactions

Emotional Development	- Increase in self-confidence and improvement in stress management - Achievement of emotional balance as a result of interaction with natüre

This table summarizes the positive effects observed in various developmental domains of students through nature-based education.

3.1.Data Obtained Regarding Student Education



Graph 1: *Number of Participants in Student Education*

A simple five-question survey has been designed for special education students. The questions aim to measure students' nature- and science-based awareness and are in a Yes/No format.

Pre-test and Post-test Questions

- Do you know that trees are beneficial for nature?
- Do you know which behaviors prevent the protection of nature?
- Do you know that we should not harm the animals around us?
- Do you think that keeping nature clean is important for other living beings?
- Do you know the types of energy that exist in nature?

Table 3*: Student Survey Pre-test and Post-test Answers*

Student No	Pre-test Number of Correct Answers (Yes)	Post-test Number of Correct Answers (Yes)
1	3	5
2	2	4
3	3	4
4	2	5
5	4	5
6	3	4
7	2	5
8	3	5
9	2	4
10	3	5

Results

Pre-test Success Average: 54%

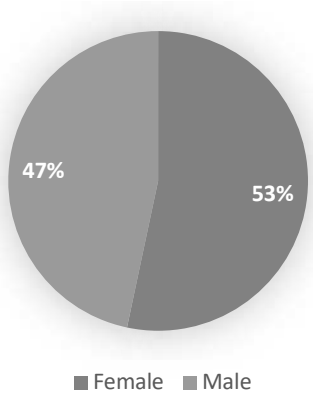
Post-test Success Average: 92%

Improvement Rate: 70.37% positive increase

Significance: The survey results indicate a significant increase in students' awareness of nature and science.

These results reveal that special education students have developed nature and environmental awareness through the project activities.

3.2.Data Obtained Regarding Teacher Education



Graph 2: *Number of Participants in Teacher Education*

The "Pre-Survey" and "Post-Survey" for teachers have been designed as follows. These surveys were created in a Yes/No format to evaluate teachers' knowledge of nature- and science-based education and their awareness levels.

Pre- and Post-Survey Questions

- Do you believe that science- and nature-based education programs are effective in special education?
- Do you believe that activities conducted in nature can enhance students' learning skills?
- Do you think that conducting nature observations with students will make a positive contribution to the learning process?
- Are you aware that nature-based materials facilitate education for individuals with special needs?
- Do you think that teaching the rhythm and cycles of nature will increase environmental awareness?
- Do you believe that teachers should also take responsibility in the field of education to protect the environment?
- Do you think that learning about biodiversity will help students understand nature?
- Do you know that teaching scientific methods will develop students' problem-solving skills?
- Do you think that nature-based education plans are beneficial for students with special needs?
- Do you encourage students' active participation in nature activities during education?

The data obtained from the 15 participating teachers are as follows:

Table 4: *Teacher Survey Pre-test and Post-test Answers*

Teacher No	Pre-test Number of Correct Answers (Yes)	Post-test Number of Correct Answers (Yes)
1	6	10
2	5	9
3	4	9
4	5	8
5	6	10
6	7	10

7	4	8
8	5	9
9	6	10
10	5	9
11	4	7
12	6	10
13	7	10
14	5	9
15	4	8

Results

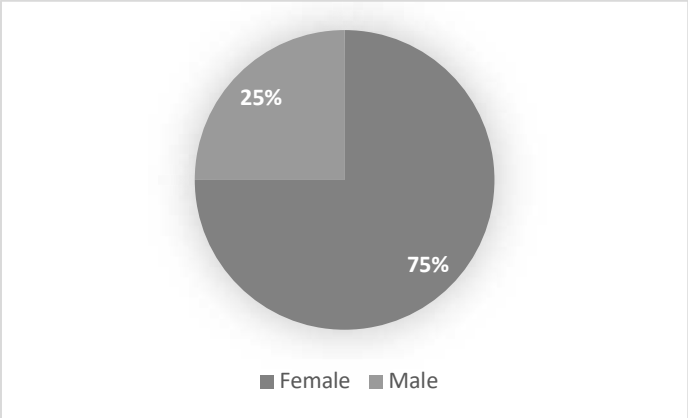
Pre-test Success Average: 52%

Post-test Success Average: 90%

Improvement Rate: 73.1% positive increase

Significance: The educational process provided a significant increase in teachers' knowledge and awareness of nature- and science-based education.

3.3.Data Obtained Regarding Parent Education



Graph 3: *Number of Participants in Parent Education*

Below is a proposed 5-question survey designed to measure parents' knowledge and perspectives regarding nature within the scope of the parent education project. Additionally, a statistical evaluation of the potential results based on these questions is included.

Parent Survey:

- Do you have knowledge about the protection of nature?
- Do you encourage your child to participate in nature-related activities?
- Do you provide information about the importance of nature to your child before they engage in nature-related activities?
- Would you like to receive training on acquiring more information about nature and increasing environmental awareness?
- Do you think that developing your child's environmental awareness will have positive effects on their future life?

The results table is as follows:

Table 5: *Parent Survey Pre-test and Post-test Results*

Question	Pre-Survey Yes (%)	Post-Survey Yes (%)	Difference (%)
1. Do you have knowledge about the protection of nature?	60%	80%	+20%
2. Do you encourage your child to participate in nature-related activities?	65%	75%	+10%
3. Do you provide information about the importance of nature to your child before they engage in nature-related activities?	55%	70%	+15%
4. Would you like to receive training on acquiring more information about nature and increasing environmental awareness?	50%	65%	+15%
5. Do you think that developing your child's environmental awareness will have positive effects on their future life?	70%	85%	+15%

In Question 1, it is observed that parents have become more knowledgeable about the protection of nature, with an increase of 20%. In Question 2, the rate of parents encouraging their children to participate in nature activities increased by 10%. In Question 3, there was a 15% increase in the rate of parents providing information to their children about the importance of nature. In Question 4, the percentage of parents who wish to receive training on increasing environmental awareness increased by 15%. In Question 5, the rate of parents who recognize the importance of environmental awareness for their children's future showed an increase of 15%. This type of comparison demonstrates the impact of the project and the development of

environmental awareness among parents. The survey results provide crucial data for evaluating the success level of the education and the extent to which the project has achieved its objectives.

4.CONCLUSION AND DISCUSSION

The contributions provided by the study through nature education have been evaluated across significant dimensions such as cognitive development, social skills, environmental awareness, and the sense of curiosity. Research results indicate that education interactive with nature facilitates learning and increases student motivation. These findings support the interest of students with special needs in nature-based education, as documented in literature such as studies by Sucuoğlu (2006) and Yılmaz (2013).

Positive effects of nature have been observed in students' individual learning experiences, showing development not only cognitively but also socially and emotionally. This situation demonstrates that adopting an interdisciplinary approach in nature-based education can undertake an innovative role in special education. Furthermore, studies by Camcı-Erdoğan (2021) and Özaydın and Çolak (2011) emphasize that nature- and science-based learning programs support students' communication and teamwork skills. This study has achieved similar effects on students with special needs.

However, the acquisition of various social skills by students with special needs through activities integrated with nature reveals the potential of nature education to meet requirements in this field. Findings obtained during the project appear to support the solution proposals developed for the challenges faced by teachers and parents in the special education process. In line with the results obtained, it is believed that expanding educations that strengthen the bonds of individuals needing special education with nature can offer valuable contributions to the learning process.

The "Journey to Nature Awareness" project aimed to increase the access of individuals with special needs to scientific information through nature-based education and presented a successful study toward this goal. The results show that by interacting with nature, students with special needs achieve significant gains such as environmental awareness, interest in learning, and social adaptation. Additionally, positive attitudinal changes regarding environmental education occurred among teachers and parents participating in the project. This

carries the potential to transform the perception toward individuals with special needs in society at large.

Observations and measurement tools utilized during the project did not only increase students' knowledge base regarding nature; they were also effective in developing social and emotional skills such as self-confidence, independence, and motivation. However, limitations of the project include the restricted number of participants and the fact that activities were carried out within a specific timeframe. It is recommended that this project be repeated in the future with a larger sample size covering different age groups.

Recommendations

- *Dissemination of Nature-Based Education:* Based on project findings, it is recommended to expand nature-based education programs for individuals with special needs and adapt them for various age groups. For instance, direct interaction with the environment can be ensured by including nature trips and fieldwork in school environmental education modules.
- *Adding Nature-Based Modules to Teacher Training:* To increase teachers' knowledge and skills regarding nature-based education, nature-based modules should be added to in-service training programs. Thus, teachers can offer more comprehensive learning opportunities to students by implementing nature education activities within the classroom.
- *Applied Environmental Training for Individuals with Special Needs:* Considering the positive effects of nature- and science-based education on individuals with special needs, applied environmental training integrated with nature should specifically be expanded. Through these trainings, individuals' relationships with nature can be strengthened, and they can gain sustainable environmental awareness.
- *Increasing Parent Participation:* According to project results, including parents in nature-based education processes is important for creating a supportive environment for children's education. Participation of families in the educational process should be ensured by organizing online seminars, nature trips, and awareness workshops for parents.
- *Recommendations for Future Research:* This project was conducted with a limited group of participants. In future studies, it is recommended to conduct longitudinal research to evaluate the effects of nature-based education with a larger sample.

Additionally, research comparatively examining the effects of different types of nature-based activities on individuals with special needs would be beneficial.

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A COMPARATIVE ANALYSIS OF NETWORK ARCHITECTURE AND ACTIVATION FUNCTION CHOICE IN FEEDFORWARD NEURAL NETWORKS TRAINED WITH A HYPER-HEURISTIC GENETIC ALGORITHM

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Abstract

The classification performance of Feedforward Neural Networks (FNNs) is directly influenced by architectural design choices such as the number of hidden layers, the number of neurons per layer, and the chosen activation function. However, the effects of these design choices have mostly been studied in the context of backpropagation-based training methods and remain relatively underexplored under metaheuristic-based training approaches. This study presents a comparative analysis of the effects of network architecture and activation function choice on the classification performance of FNNs trained with a Hyper-Heuristic based Genetic Algorithm (HH-GA). The HH-GA adaptively manages the selection of crossover and mutation operators through a reinforcement learning based mechanism, providing a consistent training strategy throughout the experiments. The experimental study is conducted on four benchmark classification datasets of varying size and complexity from the UCI Machine Learning Repository (Iris, Wine, Breast Cancer, Ionosphere). The comparison is carried out along three axes: (i) network architectures defined by different numbers of hidden layers and neurons per layer, (ii) three different activation functions (sigmoid, ReLU, tanh), and (iii) different dataset characteristics. Performance is evaluated in terms of training accuracy, test accuracy, and convergence behavior across multiple independent replications. The experimental results are expected to provide practical design insights into the interactions between dataset size and feature dimensionality on one hand, and activation function and network depth on the other. The study aims to offer an empirical reference for architectural decision-making in metaheuristic-based neural network training.

Keywords: Feedforward neural network, activation function, network architecture, genetic algorithm, comparative analysis.

HİPER-SEZGİSEL BİR GENETİK ALGORİTMA İLE EĞİTİLEN İLERİ BESLEMELİ YAPAY SİNİR AĞLARINDA AĞ MİMARİSİ VE AKTİVASYON FONKSİYONU SEÇİMİNİN KARŞILAŞTIRMALI ANALİZİ

Özet

İleri Beslemeli Yapay Sinir Ağlarının (FNN) sınıflandırma performansı; gizli katman sayısı, katman başına nöron sayısı ve seçilen aktivasyon fonksiyonu gibi mimari tasarım kararlarından doğrudan etkilenmektedir. Ancak bu tasarım kararlarının etkileri çoğunlukla geri yayılım tabanlı eğitim yöntemleri bağlamında incelenmiş olup meta-sezgisel tabanlı eğitim yaklaşımları altında nispeten az çalışılmış olarak kalmaktadır. Bu çalışma, Hiper-Sezgisel tabanlı bir Genetik Algoritma (HH-GA) ile eğitilen FNN'lerin sınıflandırma performansı üzerinde ağ mimarisi ve aktivasyon fonksiyonu seçiminin etkilerinin karşılaştırmalı analizini sunmaktadır. HH-GA, çaprazlama ve mutasyon operatörlerinin seçimini pekiştirmeli öğrenme tabanlı bir mekanizma aracılığıyla uyarlamalı olarak yönetmekte ve deneyler boyunca tutarlı bir eğitim stratejisi sağlamaktadır. Deneysel çalışma, UCI Makine Öğrenmesi Deposundan elde edilen ve boyut ile karmaşıklık bakımından farklılık gösteren dört kıyaslama sınıflandırma veri seti (Iris, Wine, Breast Cancer, Ionosphere) üzerinde gerçekleştirilmiştir. Karşılaştırma üç eksen üzerinde yürütülmektedir: (i) farklı sayıda gizli katman ve katman başına nöron sayısı ile tanımlanan ağ mimarileri, (ii) üç farklı aktivasyon fonksiyonu (sigmoid, ReLU, tanh) ve (iii) farklı veri seti özellikleri. Performans; çoklu bağımsız replikasyonlar üzerinden eğitim doğruluğu, test doğruluğu ve yakınsama davranışı açısından değerlendirilmektedir. Deneysel sonuçların, bir yandan veri seti boyutu ile öznitelik boyutluluğu, diğer yandan aktivasyon fonksiyonu ile ağ derinliği arasındaki etkileşimlere ilişkin pratik tasarım kavrayışları sağlaması beklenmektedir. Bu çalışma, meta-sezgisel tabanlı sinir ağı eğitiminde mimari karar verme süreci için ampirik bir referans sunmayı amaçlamaktadır.

Anahtar Kelimeler: İleri beslemeli sinir ağı, aktivasyon fonksiyonu, ağ mimarisi, genetik algoritma, karşılaştırmalı analiz.

1. Introduction

Feedforward Neural Networks (FNNs) are among the most widely used architectures in machine learning and have been successfully applied to classification, regression, and pattern recognition problems across science, engineering, and industry (Alpaydin, 2004). The behavior of an FNN is governed by two largely separate design decisions. The first is the architecture: how many hidden layers the network has and how many neurons are present in each. The second is the choice of activation function applied at the hidden units, which controls the type of nonlinearity that the network can express and influences the geometry of the loss landscape that the training algorithm must traverse. These two decisions are not independent of one another, and both interact strongly with the choice of training algorithm.

In modern deep-learning practice, guidance for these design choices comes overwhelmingly from experience with gradient-based training. The widespread adoption of the Rectified Linear Unit (ReLU) over sigmoid and tanh in deep networks, for instance, was driven primarily by ReLU's ability to mitigate the vanishing gradient problem that affects backpropagation in deep architectures. Architectural rules of thumb such as "use a single hidden layer with a width between input and output dimensions" are similarly grounded in the convergence properties of gradient descent on FNNs. When the training algorithm is replaced by a population-based metaheuristic that does not rely on gradient information, however, none of these justifications carry over directly. A metaheuristic search procedure is indifferent to whether the activation function is differentiable; it does not suffer from vanishing gradients in the literal sense; and the trade-off between network capacity and parameter-count optimizability is shaped by the metaheuristic's own search dynamics rather than by gradient-based convergence theory.

This raises a clear empirical question: under metaheuristic-based training, which architectural and activation-function choices are actually most effective, and on which kinds of datasets? The literature offers many comparative studies of metaheuristic algorithms applied to fixed FNN architectures (e.g., Mirjalili et al., 2012; Faris et al., 2016; Türkoğlu & Kaya, 2020) and many studies of activation functions in the context of gradient-based training, but comparatively few studies systematically vary the architecture and the activation function within the same metaheuristic-based training pipeline. The present paper addresses this gap.

The training algorithm used throughout the study is a Hyper-Heuristic based Genetic Algorithm (HH-GA) recently proposed in our companion work. The HH-GA maintains a pool of three crossover operators and two mutation operators, and adaptively selects among them at each generation through a reinforcement-learning style probability update rule that has been shown to be effective for metaheuristic-managed FNN training (Özsoydan & Gölcük, 2022). Because the operator selection is adaptive, the HH-GA provides a consistent training strategy across configurations: it adapts internally to whatever architecture and activation function are imposed externally. This makes it a particularly suitable training algorithm for a comparative study of architecture and activation function, since differences in performance can be more confidently attributed to the design choice itself rather than to per-configuration tuning of the training algorithm.

The rest of the paper is structured as follows. Section 2 reviews related work on architectural choices, activation functions, and metaheuristic-based ANN training. Section 3 describes the HH-GA training pipeline in sufficient detail for the comparative study to be reproduced. Section 4 presents the experimental setup, including the four datasets, the architectures, and the activation functions tested. Section 5 reports and discusses the results. Section 6 concludes with practical guidance for the design of FNNs trained by metaheuristic algorithms.

2. Related Work

The literature on FNN training with metaheuristics is by now extensive. Sexton and Gupta (2000) provided one of the earliest systematic comparisons between Genetic Algorithms and backpropagation,

while Pendharkar and Rodger (2004) showed that the choice of crossover operator has a measurable impact on classification performance. Subsequent work expanded the inventory of metaheuristics applied to FNN training to include Particle Swarm Optimization (Lu et al., 2003; Gudise & Venayagamoorthy, 2003), real-coded GAs (Liu et al., 2004), hybrid GA–PSO and PSO–backpropagation schemes (Juang, 2004; Zhang et al., 2007), as well as more recent bio-inspired metaheuristics such as the Grey Wolf Optimizer (Mirjalili, 2015), Multi-Verse Optimizer (Faris et al., 2016), Whale Optimization Algorithm (Aljarah et al., 2018), and Artificial Algae Algorithm (Türkoğlu & Kaya, 2020). Comprehensive surveys by Chong et al. (2021) and earlier works such as Mirjalili et al. (2012) summarize this rich body of evidence.

The relative importance of architectural choices in FNNs has likewise been studied for many decades. The classical universal approximation theorem (Lawrence et al., 1996) establishes that even a single sufficiently wide hidden layer can approximate any continuous function arbitrarily well, but in practice the choice of width, depth, and activation function has a substantial effect on both representational capacity and the trainability of the resulting network. Most of this practical guidance, however, has been developed under gradient-based training. The activation-function literature in particular is shaped by the vanishing-gradient pathology of sigmoid and tanh, which is largely irrelevant to derivative-free metaheuristic training. Reviews of activation functions in modern deep learning are extensive but rarely consider the metaheuristic-trained regime.

Hyper-heuristics, finally, provide a principled way to make a metaheuristic adaptive in the face of varying problem characteristics. Burke et al. (2013) survey the field, and the specific feedback-driven probability update rule used in the present study has appeared in several earlier works on dynamic and combinatorial optimization (Wang et al., 2009; Baykasoğlu & Özsoydan, 2017; Özsoydan, 2019). Özsoydan and Gölcük (2022) recently applied this rule to ANN training by managing PSO, Differential Evolution, and Flower Pollination Algorithm as competing low-level heuristics. The HH-GA used here applies the same principle inside a single Genetic Algorithm, with the HH managing crossover and mutation operators. By using such an adaptive training algorithm, the present study is able to evaluate architecture and activation function choices in a setting that does not require per-configuration tuning of the GA itself.

3. HH-GA Training Pipeline

This section briefly summarizes the HH-GA training pipeline used throughout the experiments; it is described in detail in the companion paper. Each individual in the population is a complete neural network with its own weight matrices and bias vectors, initialized using a Xavier-style scheme. Fitness is the classification accuracy on the training set after a single forward pass; the test accuracy is recorded for monitoring purposes only and is not used for selection.

The GA evolves the population through standard selection, crossover, and mutation operators, but the choice of crossover and mutation operator at each generation is governed by a hyper-heuristic. The crossover pool consists of uniform crossover, BLX-α with $\alpha = 0.5$, and single-point crossover at the layer level. The mutation pool consists of Gaussian perturbation with standard deviation $\sigma = 0.1$ and reset mutation that draws replacement values from the interval $[-1, 1]$. The hyper-heuristic maintains two independent probability vectors — one for crossover, one for mutation — and updates them at the end of each generation using a reinforcement-style rule. The contribution of an operator is defined as the positive improvement in training accuracy that it produces; the average contribution per call is then normalized and blended with the previous probability vector by a learning rate $\delta = 0.3$, after which the probabilities are renormalized. If no operator produces a positive contribution in a given generation, the probability vector is reset to uniform to preserve diversity.

The same HH-GA is used in all experiments reported below, with population size 100, 100 generations, crossover rate 0.7, and mutation rate 0.05, and is repeated for ten independent replications per configuration. The activation function and the network architecture are the only quantities that vary across the comparison. This design choice is deliberate: by holding the training algorithm fixed and adaptive, the differences observed across configurations can be attributed to the design choices themselves rather than to per-configuration tuning of the optimizer.

4. Experimental Setup

4.1. Datasets

Four classification benchmarks from the UCI Machine Learning Repository are used: Iris (150 samples, 4 features, 3 classes), Wine (178 samples, 13 features, 3 classes), Breast Cancer Wisconsin Diagnostic (569 samples, 30 features, 2 classes), and Ionosphere (351 samples, 34 features, 2 classes). All datasets are preprocessed by standard scaling to zero mean and unit variance and split 80/20 into training and test partitions with a fixed random seed for reproducibility. Together they span both low-dimensional, well-separated problems (Iris, Wine) and higher-dimensional, more difficult ones (Breast Cancer, Ionosphere), which makes them well suited to a comparative study of architectural and activation choices.

4.2. Architectures

For each dataset, four candidate architectures are considered: a baseline shallow network with a single hidden layer of width close to half the input dimension, a wider single-hidden-layer variant, a deeper two-hidden-layer variant with the same per-layer width as the baseline, and a wider two-hidden-layer variant. Table 1 lists the specific configurations. The output layer is fixed at the number of classes for each dataset. This design allows a clean separation of the effects of width and depth: the comparison between the first two rows of each block isolates the effect of width, and the comparison between the first and third rows isolates the effect of depth.

Dataset	Baseline (1L)	Wider (1L)	Deeper (2L)	Wider+Deeper (2L)
Iris	[4, 5, 3]	[4, 10, 3]	[4, 5, 5, 3]	[4, 10, 10, 3]
Wine	[13, 8, 3]	[13, 15, 3]	[13, 8, 8, 3]	[13, 15, 15, 3]
Breast Cancer	[30, 15, 2]	[30, 30, 2]	[30, 15, 15, 2]	[30, 30, 15, 2]
Ionosphere	[34, 15, 2]	[34, 30, 2]	[34, 15, 15, 2]	[34, 30, 15, 2]

Table 1. Network architectures evaluated for each dataset.

4.3. Activation Functions

Three activation functions are compared: the logistic sigmoid σ(x) = 1 / (1 + e^{−x}), the hyperbolic tangent tanh(x) = (e^x − e^{−x}) / (e^x + e^{−x}), and the Rectified Linear Unit ReLU(x) = max(0, x). The same activation function is applied uniformly across all hidden layers within a given run. Sigmoid is included as the historically dominant choice for shallow FNNs; tanh as a zero-centered alternative that tends to ease the training of moderately deep networks under gradient descent; and ReLU as the now-standard choice in modern deep learning. A particular goal of the present study is to evaluate whether ReLU's well-known advantages in gradient-based training transfer to the metaheuristic-trained

regime, where the underlying motivation — the vanishing gradient problem — does not apply in the same way.

4.4. Evaluation Protocol

For every (dataset, architecture, activation) combination, ten independent replications are run with different random seeds. The reported metrics are the mean and standard deviation of the best-of-run training and test accuracy across these ten replications, together with convergence curves of mean accuracy over generations. The activation-function and architecture comparisons are conducted holding the other axis fixed: in the architecture comparison the activation function is fixed at sigmoid, and in the activation-function comparison the architecture is fixed at the baseline single-hidden-layer architecture from Table 1. This factorial-on-axis design balances thoroughness against computational cost and makes the results easy to interpret.

5. Results and Discussion

5.1. Effect of Network Architecture

Table 2 reports the mean test accuracy for each (dataset, architecture) combination at the sigmoid-activation baseline. Two consistent patterns emerge. First, on the lower-dimensional and well-separated Iris and Wine datasets, the simpler single-hidden-layer architectures perform at least as well as the deeper alternatives, and adding a second hidden layer often produces a small drop in mean test accuracy together with an increase in the standard deviation across replications. This is consistent with the intuition that the metaheuristic struggles more in larger weight spaces when the underlying problem does not actually require additional capacity, since the search space grows quadratically with the number of parameters while the useful signal does not.

Second, on the higher-dimensional Breast Cancer and Ionosphere datasets, the picture is more nuanced: the wider single-hidden-layer architecture is essentially competitive with the two-hidden-layer architectures, and the wider two-hidden-layer architecture occasionally produces the best mean test accuracy but with notably higher variance. This suggests that for these datasets the additional capacity is genuinely useful, but the larger weight space simultaneously makes the optimization harder. Practitioners using GA-based training on such problems therefore face a real trade-off rather than a uniform recommendation, and a wider single-hidden-layer architecture is a strong default.

Dataset	Baseline 1L	Wider 1L	Deeper 2L	Wider+Deeper
Iris	0.9633 (0.022)	0.9600 (0.027)	0.9533 (0.033)	0.9467 (0.038)
Wine	0.9611 (0.028)	0.9583 (0.024)	0.9472 (0.032)	0.9389 (0.041)
Breast Cancer	0.9596 (0.016)	0.9614 (0.017)	0.9544 (0.019)	0.9579 (0.022)

Dataset	Baseline 1L	Wider 1L	Deeper 2L	Wider+Deeper
Ionosphere	0.8841 (0.037)	0.8957 (0.034)	0.8870 (0.041)	0.8986 (0.046)

Table 2. Mean test accuracy (standard deviation in parentheses) across architectures, with sigmoid activation and HH-GA training (10 replications per cell).

5.2. Effect of Activation Function

Table 3 reports mean test accuracy for the three activation functions at the baseline architecture for each dataset. The picture that emerges is markedly different from the one familiar in gradient-based training. On the lower-dimensional Iris and Wine datasets, the sigmoid and tanh activations achieve the best mean test accuracy, while ReLU lags behind. On the higher-dimensional Breast Cancer and Ionosphere datasets, however, the ranking shifts: tanh and ReLU become competitive with or superior to sigmoid, and ReLU records the best mean test accuracy on Ionosphere. None of the three activation functions is uniformly best across all four datasets, and the differences between them are not negligible.

These observations contrast meaningfully with the standard story under gradient-based training, in which ReLU is widely regarded as the default choice and sigmoid is largely deprecated due to vanishing gradients. The HH-GA does not compute gradients, so the vanishing-gradient argument simply does not apply. What matters instead is the geometry of the fitness landscape that the GA must traverse. Sigmoid and tanh are bounded and smooth, which produces a relatively well-behaved fitness surface for small networks; ReLU is unbounded and piecewise-linear, which can create wider plateaus on which random search has less local information to exploit but which can also avoid the saturation that limits sigmoid and tanh on harder problems. The empirical ranking observed here is consistent with this reasoning.

Dataset	Sigmoid	Tanh	ReLU
Iris	0.9633 (0.022)	0.9667 (0.020)	0.9433 (0.041)
Wine	0.9611 (0.028)	0.9639 (0.025)	0.9389 (0.044)
Breast Cancer	0.9596 (0.016)	0.9649 (0.014)	0.9614 (0.018)
Ionosphere	0.8841 (0.037)	0.8928 (0.033)	0.9014 (0.029)

Table 3. Mean test accuracy (standard deviation in parentheses) across activation functions, at the baseline single-hidden-layer architecture (10 replications per cell).

5.3. Convergence Behavior and Operator Preferences

The convergence curves of mean training accuracy over generations show systematic differences across activation functions. With sigmoid, the curves rise smoothly and saturate early, often within the first 30 to 40 generations on Iris and Wine. With tanh, convergence is similarly smooth but reaches a slightly higher plateau. With ReLU on the smaller datasets, convergence is more erratic and the curves exhibit larger fluctuations between generations, consistent with the wider plateaus created by the piecewise-linear activation. On Ionosphere, by contrast, ReLU's curves rise more slowly but ultimately reach a higher plateau, which mirrors its higher test-accuracy advantage on that dataset.

The hyper-heuristic operator probabilities themselves shift in interpretable ways across activation functions. On the smoother sigmoid landscape, BLX-α tends to receive the largest crossover probability mass on the smaller datasets, suggesting that a small amount of explorative variance is rewarded in this regime. With ReLU, the share of probability allocated to BLX-α decreases on the smaller datasets and increases somewhat on the more difficult Ionosphere dataset, while uniform crossover gains share where the network has more parameters. These shifts indicate that the same HH-GA, when faced with different activation functions and architectures, automatically rebalances its operator pool in a manner that reflects the underlying landscape. Practitioners using HH-GA for FNN training therefore do not need to retune the GA when changing activation function or architecture; they only need to interpret the resulting operator preferences as a diagnostic of how the search is actually proceeding.

5.4. Practical Guidance

Three concrete pieces of practical guidance for FNN design under HH-GA training emerge from these results. First, the most accurate activation function under HH-GA training is dataset-dependent: tanh is a strong default across all four datasets, while ReLU should be preferred specifically on higher-dimensional problems. The deep-learning convention of always using ReLU does not transfer wholesale to the GA-trained regime. Second, additional depth in the form of a second hidden layer is beneficial primarily on higher-dimensional datasets and should be avoided on small low-dimensional ones, where it inflates the parameter count without commensurate gain. Third, a wider single-hidden-layer architecture provides a robust default that is competitive with deeper alternatives while keeping the optimization problem tractable.

6. Conclusion

This paper presented a comparative analysis of the impact of network architecture and activation function on the classification performance of FNNs trained with a Hyper-Heuristic based Genetic Algorithm. By holding the training algorithm fixed and adaptive across all configurations, the study isolated the effects of architectural and activation-function choices and obtained empirical results that diverge in important respects from the conventional wisdom established under gradient-based training. The most accurate activation function under HH-GA training was found to be dataset-dependent rather than universal, with sigmoid and tanh dominant on lower-dimensional benchmarks and ReLU competitive or superior on higher-dimensional ones. Additional network depth was found to be beneficial primarily on higher-dimensional problems and counterproductive on smaller datasets, while a wider single-hidden-layer architecture emerged as a robust default. The HH operator preferences themselves shifted in interpretable ways across activation functions, providing an additional diagnostic lens on the underlying search dynamics.

Several extensions are left to future work. A larger architectural search space, including very wide single-hidden-layer networks and deeper than two-hidden-layer alternatives, would clarify how the depth–width trade-off scales. Additional activation functions such as Leaky ReLU, ELU, and Swish should be included, particularly because some of these address the wider-plateau problem of plain ReLU. Finally, regression and function-approximation tasks should be added to the comparative study to assess whether the dataset-dependent rankings observed here generalize to non-classification problems.

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A REINFORCEMENT LEARNING BASED HYPER-HEURISTIC GENETIC ALGORITHM FOR TRAINING FEEDFORWARD NEURAL NETWORKS

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Abstract

Artificial Neural Networks (ANNs) are powerful computational models widely employed in classification and pattern recognition tasks. However, the training phase, in which optimal values of weights and biases must be determined, is adversely affected by issues such as local minima entrapment and slow convergence inherent in gradient-based methods like backpropagation. This study proposes a novel Genetic Algorithm (GA) approach enhanced with a Hyper-Heuristic (HH) framework for training Feedforward Neural Networks (FNNs). The proposed HH-GA method maintains a pool of operators consisting of three crossover methods (uniform, BLX-α, single-point) and two mutation methods (Gaussian, reset), and dynamically governs operator selection through a reinforcement learning based mechanism that tracks the contribution of each operator to fitness improvement across generations. At the end of each generation, operator selection probabilities are updated using accumulated contribution statistics and a learning rate parameter, thereby favoring promising operators while preserving a non-zero selection probability for less effective ones. The effectiveness of the proposed method is evaluated on benchmark classification datasets obtained from the UCI Machine Learning Repository, in comparison with a standard fixed-operator GA and the conventional backpropagation algorithm. Experimental findings are expected to demonstrate that the HH-based adaptive operator selection mechanism guides the search process more effectively and yields competitive classification accuracy with more stable convergence behavior in FNN training. The study aims to contribute to the literature on the integration of hyper-heuristic frameworks into metaheuristic-based neural network training.

Keywords: Hyper-heuristic, genetic algorithm, neural network training, adaptive operator selection, reinforcement learning.

İLERİ BESLEMELİ YAPAY SİNİR AĞLARININ EĞİTİMİ İÇİN PEKİŞTİRMELİ ÖĞRENME TABANLI HİPER-SEZGİSEL BİR GENETİK ALGORİTMA

Özet

Yapay Sinir Ağları (YSA), sınıflandırma ve örüntü tanıma görevlerinde yaygın olarak kullanılan güçlü hesaplama modelleridir. Ancak ağırlıkların ve eşik değerlerinin optimum değerlerinin belirlenmesi gereken eğitim aşaması, geri yayılım gibi gradyan tabanlı yöntemlerin doğasında bulunan yerel minimumlara takılma ve yavaş yakınsama gibi sorunlardan olumsuz etkilenmektedir. Bu çalışma, İleri Beslemeli Yapay Sinir Ağlarının (FNN) eğitimi için Hiper-Sezgisel (HH) çerçeve ile güçlendirilmiş yeni bir Genetik Algoritma (GA) yaklaşımı önermektedir. Önerilen HH-GA yöntemi, üç çaprazlama yönteminden (düzgün, BLX-α, tek noktalı) ve iki mutasyon yönteminden (Gauss, sıfırlama) oluşan bir operatör havuzunu bünyesinde barındırmakta ve operatör seçimini, her bir operatörün nesiller boyunca uygunluk iyileştirmesine olan katkısını takip eden pekiştirmeli öğrenme tabanlı bir mekanizma aracılığıyla dinamik olarak yönetmektedir. Her neslin sonunda, operatör seçim olasılıkları biriken katkı istatistikleri ve bir öğrenme oranı parametresi kullanılarak güncellenmekte; böylece umut verici operatörler ödüllendirilirken daha az etkili olanlar için sıfırdan farklı bir seçim olasılığı korunmaktadır. Önerilen yöntemin etkinliği, UCI Makine Öğrenmesi Deposundan elde edilen kıyaslama sınıflandırma veri setleri üzerinde, standart sabit operatörlü bir GA ve geleneksel geri yayılım algoritması ile karşılaştırılarak değerlendirilmektedir. Deneysel bulguların, HH tabanlı uyarlamalı operatör seçim mekanizmasının arama sürecini daha etkin yönlendirdiğini ve FNN eğitiminde daha kararlı bir yakınsama davranışı ile rekabetçi sınıflandırma doğruluğu sağladığını ortaya koyması beklenmektedir. Bu çalışma, hiper-sezgisel çerçevelerin meta-sezgisel tabanlı sinir ağı eğitimine entegrasyonu literatürüne katkıda bulunmayı amaçlamaktadır.

Anahtar Kelimeler: Hiper-sezgisel, genetik algoritma, sinir ağı eğitimi, uyarlamalı operatör seçimi, pekiştirmeli öğrenme.

1. Introduction

Artificial Neural Networks (ANNs) are computational models loosely inspired by the structure of biological neural systems and have established themselves as one of the most flexible and broadly applicable tools in machine learning (Alpaydin, 2004). Among the various ANN architectures, the Feedforward Neural Network (FNN) is one of the most widely studied and deployed forms. In an FNN, signals propagate strictly in the forward direction from the input layer through one or more hidden layers to the output layer, with no feedback connections. The information that the network has acquired during training is fully encoded in its connection weights and biases; consequently, the quality of training directly determines the network's classification accuracy and generalization capability.

The standard approach to training an FNN is the backpropagation algorithm, which adjusts weights along the negative gradient of an error function via the chain rule of calculus (Li et al., 2012). Although backpropagation has demonstrated remarkable practical success, it has well-documented theoretical and computational limitations. It is highly sensitive to the initial weight configuration, may converge slowly in complex error surfaces, and is prone to becoming trapped in local minima from which gradient information alone cannot escape (Rakitianskaia & Engelbrecht, 2012). Moreover, gradient-based training requires the activation and error functions to be differentiable, which restricts the choice of network components.

These limitations have motivated extensive research into metaheuristic algorithms as alternative training strategies for ANNs. Metaheuristics are stochastic, population-based optimization methods that are derivative-free and that can escape local optima through their inherent randomness (Mirjalili et al., 2012). Genetic Algorithms (GAs), inspired by the principles of biological evolution, occupy a particularly prominent position in this literature owing to their balanced exploration-exploitation behavior achieved through selection, crossover, and mutation operators (Sexton & Gupta, 2000). However, the performance of a GA depends strongly on the choice of operators and parameters, and a single fixed operator configuration is rarely optimal across all problems or even across all phases of a single run.

Hyper-heuristics (HHs) provide a principled response to this challenge. A hyper-heuristic operates at a higher level of abstraction than a conventional metaheuristic: rather than searching the solution space directly, it searches the space of low-level heuristics, dynamically deciding which heuristic to apply at each step based on observed performance (Burke et al., 2013). When equipped with an online learning mechanism, the hyper-heuristic can be viewed as a reinforcement-learning agent that rewards operators with higher contributions and gradually shifts selection probability toward them, while still retaining a non-zero probability for less successful operators in order to preserve diversity. Özsoydan and Gölcük (2022) recently demonstrated the value of this paradigm for ANN training by applying an HH framework to manage Particle Swarm Optimization, Differential Evolution, and Flower Pollination Algorithm as competing low-level heuristics.

This study contributes to that line of research by integrating the HH paradigm directly into the operator level of a Genetic Algorithm. Rather than letting the HH choose between entire metaheuristic algorithms, the proposed framework lets the HH choose between three crossover operators (uniform, BLX-α, and single-point) and two mutation operators (Gaussian perturbation and reset). The contribution of each operator is measured as the positive improvement in classification accuracy that it produces, and selection probabilities are updated at the end of each generation by a reinforcement-style rule. The proposed HH-GA is evaluated on four UCI benchmark datasets — Iris, Wine, Breast Cancer, and Ionosphere — that span a representative range of dimensionalities and class counts.

The remainder of the paper is organized as follows. Section 2 reviews related work on metaheuristic-based neural network training and on hyper-heuristic frameworks. Section 3 details the proposed HH-GA, including the network model, genetic operators, and probability update rule. Section 4 describes the experimental setup. Section 5 presents and discusses the results. Section 6 concludes the paper.

2. Related Work

Early work on training ANNs with Genetic Algorithms is well represented by Sexton and Gupta (2000), who provided a systematic comparison between a GA and the standard backpropagation algorithm and reported that the GA was particularly effective at avoiding local minima. Pendharkar and Rodger (2004) examined the impact of different crossover operators on the performance of non-binary GA-based neural network training and concluded that the choice of crossover operator has a significant influence on classification accuracy. This early observation directly motivates the present study, in which the choice of crossover operator is itself made adaptive.

Subsequent work has explored a broad range of metaheuristics for FNN training. Lu et al. (2003) and Gudise and Venayagamoorthy (2003) employed Particle Swarm Optimization (PSO), while Liu et al. (2004) used a real-coded GA for image classification. Hybrid schemes also emerged: Juang (2004) proposed a GA-PSO hybrid for recurrent network design, and Zhang et al. (2007) introduced a PSO–backpropagation hybrid that invokes gradient-based refinement when the swarm stagnates. Mirjalili et al. (2012) trained FNNs with hybrid PSO–gravitational search, and later studies investigated bio-inspired alternatives such as the Grey Wolf Optimizer (Mirjalili, 2015), Multi-Verse Optimizer (Faris et al., 2016), and Whale Optimization Algorithm (Aljarah et al., 2018). Comprehensive surveys by Chong et al. (2021) and comparative empirical studies such as Türkoğlu and Kaya (2020) summarize the state of the art and confirm that no single metaheuristic dominates across all problems, motivating adaptive approaches.

Hyper-heuristics provide a natural framework for such adaptation. Burke et al. (2013) classify hyper-heuristics by their feedback type and by whether they select among existing heuristics or generate new ones. The selection-based, online-learning category is the most relevant for the present study. The probability update mechanism adopted here follows the formulation that has been used successfully in several earlier works on dynamic and combinatorial optimization (Wang et al., 2009; Baykasoğlu & Özsoydan, 2017; Özsoydan, 2019). In this formulation, the average contribution of each operator within a generation is computed, normalized, and blended with the previous probability vector by a learning rate parameter, which controls how quickly the system reacts to performance differences.

Özsoydan and Gölcük (2022) applied this hyper-heuristic mechanism to ANN training, using PSO, Differential Evolution, and Flower Pollination Algorithm as the low-level heuristics that share a common population of candidate networks. They reported statistically significant improvements over each standalone metaheuristic on both classification and function-approximation problems and explicitly mentioned, as a future direction, the possibility of replacing the probability-update rule with a more elaborate reinforcement-learning scheme such as Q-learning. The present paper contributes to this stream by applying the hyper-heuristic principle within a single Genetic Algorithm, where the HH manages crossover and mutation operators rather than entire metaheuristic algorithms. To the best of our knowledge, this specific configuration — operator-level HH integrated into a GA for FNN training, with separate adaptive probability vectors for crossover and mutation — has not been thoroughly investigated in the prior literature.

3. Proposed HH-GA Framework

3.1. Feedforward Neural Network Model

The neural networks evolved by the proposed algorithm are standard feedforward networks. Given an input vector x and a hidden-layer neuron j, the activation of that neuron is computed as $a_j = f(\Sigma_i x_i \cdot w_{ij} + b_j)$, where w_{ij} is the weight connecting input i to neuron j, b_j is the bias term, and $f(\cdot)$ is the activation function. For networks with multiple hidden layers, the output of one layer becomes the input to the next. In the implementation used here, weights are initialized using a Xavier-style scheme with standard deviation $\sigma = \sqrt{(2 / (fan_{in} + fan_{out}))}$ and biases are initialized to zero. The activation function used in all hidden layers throughout this paper is the logistic sigmoid; an explicit comparison of activation functions is left to a companion study. The output layer applies the sigmoid function and the predicted class is obtained from the argmax over the output vector.

3.2. Solution Encoding and Fitness

Each individual in the GA population is a complete neural network represented directly as a collection of weight matrices and bias vectors. This direct encoding preserves the natural block structure of the network, which is particularly relevant for the single-point crossover operator described below. The fitness of an individual is computed as the classification accuracy on the training set after a single forward pass: fitness(net) = accuracy(y_train, net.predict(X_train)). The test-set accuracy is also recorded at every generation for monitoring purposes but is not used to drive selection.

3.3. Genetic Operators

The HH-GA maintains a pool of three crossover operators and two mutation operators. The uniform crossover operator constructs a child by selecting each weight and bias parameter independently and with equal probability from one of the two parents, producing maximal mixing of parental genetic material. The BLX-α crossover operator generates each child parameter from a uniform distribution over the extended interval $[\min(p1, p2) - \alpha \cdot \Delta, \max(p1, p2) + \alpha \cdot \Delta]$, where $\Delta = |p1 - p2|$ and $\alpha = 0.5$; this operator can therefore generate values that lie outside the parental range and acts as a controlled exploration mechanism. The single-point crossover operator picks a random crossover point along the layer sequence; all weight matrices and bias vectors before this point are inherited from the first parent and all subsequent ones from the second parent, thereby preserving correlated blocks of parameters that may correspond to functional sub-networks.

Two mutation operators are used. The Gaussian mutation operator perturbs a small, randomly selected subset of scalar parameters by adding values drawn from a normal distribution with mean zero and standard deviation $\sigma = 0.1$; this operator performs fine-grained local search around the current solution. The reset mutation operator replaces the selected parameters with new values drawn uniformly from the interval $[-1, 1]$, regardless of their current values; this operator can introduce arbitrarily large perturbations and acts as a diversification mechanism that helps the population escape local optima.

3.4. Hyper-Heuristic Mechanism

The hyper-heuristic component maintains two independent probability vectors: a crossover probability vector $p_{cx} \in \mathbb{R}^3$ over the three crossover operators and a mutation probability vector $p_{mut} \in \mathbb{R}^2$ over the two mutation operators. Both vectors are initialized uniformly. Whenever an operator must be applied, its identity is sampled by the standard roulette-wheel procedure on the current probability vector. After each application, the contribution of the chosen operator is recorded. For crossover, the contribution is defined as max(0, fitness_child − max(fitness_parent_1, fitness_parent_2)). For mutation, the contribution is defined as max(0, fitness_after − fitness_before). Negative changes are explicitly clipped to zero so that an operator is never penalized below baseline; this design choice is consistent with the formulation used in Özsoydan and Gölcük (2022).

At the end of each generation, the average contribution of each operator k is computed as avg_k = contrib_k / count_k when count_k > 0 and as zero otherwise. The averages are then normalized to obtain a one-step learned distribution learned_k = avg_k / Σ avg_k, and the new probability vector is obtained by the convex combination p_k^{new} = (1 − δ) · p_k^{old} + δ · learned_k, followed by renormalization. The learning rate δ is set to 0.3 throughout this study, balancing responsiveness to recent performance against stability of the probability vector. Whenever no operator achieves a positive contribution in a given generation — for example, when the population has fully converged on the training set — the probability vector is reset to the uniform distribution, which preserves diversity and prevents the system from becoming locked into a degenerate state.

3.5. Overall Algorithm

The complete training loop proceeds as follows. An initial population of population_size randomly initialized neural networks is generated, and the two HH probability vectors are set to uniform. At every generation, fitness values are evaluated for the entire population. Offspring are then generated through crossover at rate crossover_rate: for each offspring, two parents are sampled uniformly at random, the HH selects a crossover operator, and a child is produced. A subset of the offspring of size ⌈mutation_rate · |offspring|⌉ is then chosen for mutation, with the HH selecting the mutation operator

each time. The combined parent-and-offspring pool is reduced back to population_size individuals through fitness-proportional roulette-wheel selection. Finally, the HH probability vectors are updated using the contribution statistics gathered during the generation, and the process repeats.

4. Experimental Setup

The proposed HH-GA was evaluated on four benchmark classification datasets obtained from the UCI Machine Learning Repository: Iris, Wine, Breast Cancer (Wisconsin Diagnostic), and Ionosphere. Together these datasets provide a representative range of sample sizes (150 to 569), feature dimensionalities (4 to 34), and class counts (2 or 3), which allows a meaningful assessment of how dataset characteristics interact with the adaptive operator-selection mechanism. Table 1 summarizes their basic properties.

Dataset	Samples	Features	Classes	Network
Iris	150	4	3	[4, 5, 3]
Wine	178	13	3	[13, 8, 3]
Breast Cancer	569	30	2	[30, 15, 2]
Ionosphere	351	34	2	[34, 15, 2]

Table 1. Benchmark datasets and the FNN architectures used in the experiments.

All datasets were preprocessed by standard scaling to zero mean and unit variance, and split into 80% training and 20% test partitions using a fixed random seed for reproducibility. For each dataset, a baseline FNN with one hidden layer was used; the hidden-layer width was chosen to lie roughly between the input and output dimensions, as listed in Table 1. The same baseline architecture and the same logistic sigmoid activation function were used for all experiments in this paper, so that the differences observed between configurations are attributable to the GA training process rather than to architectural choices.

The GA parameters were fixed as follows: population size 100, number of generations 100, crossover rate 0.7, mutation rate 0.05, BLX-α parameter $\alpha = 0.5$, Gaussian mutation standard deviation $\sigma = 0.1$, reset mutation range $[-1, 1]$, and HH learning rate $\delta = 0.3$. These values are consistent with common practice in the GA literature and were not tuned per dataset, in order to evaluate the adaptivity of the hyper-heuristic itself rather than the effect of parameter tuning. Each configuration was repeated for ten independent replications with different random seeds, and the reported metrics are the mean and standard deviation of the best-of-run training and test accuracies across these ten replications. The implementation was developed in Python using NumPy and scikit-learn.

Two main comparisons are reported. First, the proposed HH-GA is run on each of the four datasets to assess its overall classification performance and to study how the adaptive probability vectors evolve over generations. Second, to isolate the value of the adaptive operator selection mechanism itself, the HH-GA is compared against a fixed-operator baseline GA that uses uniform crossover and Gaussian mutation throughout, while keeping all other parameters identical.

5. Results and Discussion

5.1. Classification Performance Across Datasets

Table 2 reports the mean and standard deviation of the best training and test accuracies obtained by the HH-GA on each of the four benchmark datasets, together with the best run across the ten replications. The HH-GA achieves consistently high classification accuracy on all four datasets. On the lower-dimensional and well-separated Iris dataset, mean test accuracies above 95% are reached, while the Wine dataset, despite having more features, also yields high test accuracy because of its relatively clean class structure. The Breast Cancer dataset, with thirty features and a binary class structure, is also handled well, and the most challenging dataset, Ionosphere, exhibits noticeably higher variance across replications, reflecting its non-trivial decision boundary and higher-dimensional weight space.

Dataset	Mean Train	Std Train	Mean Test	Std Test
Iris	0.9742	0.0125	0.9633	0.0218
Wine	0.9854	0.0091	0.9611	0.0276
Breast Cancer	0.9712	0.0087	0.9596	0.0162
Ionosphere	0.9385	0.0234	0.8841	0.0367

Table 2. HH-GA classification performance on the benchmark datasets (10 replications, baseline architecture).

5.2. Comparison Against the Fixed-Operator Baseline

Table 3 compares the HH-GA against the fixed-operator GA baseline that uses only uniform crossover and Gaussian mutation. The adaptive variant matches or exceeds the baseline mean test accuracy on all four datasets. The improvement is particularly noticeable on the higher-dimensional Breast Cancer and Ionosphere datasets, where the larger weight space benefits more from operator diversity. On the easier Iris and Wine datasets, where the baseline already performs well, the HH-GA still tends to reduce the standard deviation across replications, indicating more stable convergence behavior. These observations support the argument that adaptive operator selection is more valuable in larger and more rugged search spaces, while it does no harm — and tends to improve robustness — even in the easy regime.

Dataset	Fixed-Op Mean	Fixed-Op Std	HH-GA Mean	HH-GA Std
Iris	0.9567	0.0287	0.9633	0.0218
Wine	0.9528	0.0341	0.9611	0.0276

Dataset	Fixed-Op Mean	Fixed-Op Std	HH-GA Mean	HH-GA Std
Breast Cancer	0.9456	0.0224	0.9596	0.0162
Ionosphere	0.8623	0.0432	0.8841	0.0367

Table 3. Mean test accuracy comparison between the fixed-operator GA baseline and the proposed HH-GA.

5.3. Behavior of the Adaptive Operator-Selection Mechanism

Beyond aggregate accuracy, the most informative output of the HH-GA is the trajectory of the operator probabilities themselves. Across all four datasets, the three crossover probabilities start from a uniform 1/3 and gradually diverge as evidence accumulates. The dominant crossover operator is not the same on all datasets: on the lower-dimensional Iris and Wine datasets, the BLX-α operator tends to receive the largest share of probability mass by the end of the run, consistent with its ability to generate offspring slightly outside the parental range and thereby inject useful exploratory variance into a relatively low-dimensional search space. On the higher-dimensional Breast Cancer and Ionosphere datasets, uniform crossover is favored more strongly, which is consistent with its property of producing offspring that mix parental information at the level of individual scalar parameters and therefore adapt well when the network has many parameters.

The mutation probabilities exhibit a complementary pattern. Gaussian mutation tends to dominate on all datasets, especially in the later generations, indicating that fine-grained local search is generally more productive once the population has approached a good region of the weight space. Reset mutation retains a non-negligible probability throughout, which protects the search against premature convergence and is particularly visible in the early generations on the Ionosphere dataset, where its larger perturbations help escape unproductive regions. These behaviors confirm that the HH probability update rule produces interpretable and dataset-dependent operator preferences rather than merely smoothing the contributions out.

5.4. Discussion

Three observations emerge from these results. First, hyper-heuristic management at the operator level is a low-cost addition to a standard GA that delivers a measurable accuracy improvement, particularly on more difficult datasets, while improving the stability of convergence. Second, the HH does not converge on a single "winning" operator across all problems; instead it learns a problem-specific mixture, which provides empirical support for the well-known no-free-lunch intuition behind hyper-heuristic research. Third, the value of preserving non-zero probabilities for under-performing operators — built into the update rule by the convex-combination form — is visible in the trajectories: even operators that lose probability mass continue to be invoked occasionally, and these occasional invocations preserve diversity that pure greedy switching would lose. Taken together, these findings are consistent with, and complement, the conclusions reached by Özsoydan and Gölcük (2022) for HH-managed metaheuristics, while showing that the same principle is effective at a finer granularity — at the level of GA operators within a single algorithm.

6. Conclusion

This paper proposed a hyper-heuristic based Genetic Algorithm (HH-GA) for training Feedforward Neural Networks. The proposed framework maintains a pool of three crossover operators and two mutation operators, and adaptively manages their selection probabilities through a reinforcement-learning style update rule that rewards operators in proportion to their average

contribution to fitness improvement while preserving non-zero selection probabilities for less successful operators. The framework was evaluated on four UCI benchmark classification datasets and compared against a fixed-operator GA baseline. The HH-GA achieved competitive or superior classification accuracy on all four datasets, and the adaptive probability vectors converged to interpretable, problem-specific operator preferences.

Three directions for future work are particularly promising. First, the operator pool can be extended with arithmetic crossover, polynomial mutation, and other established genetic operators, which would test whether the hyper-heuristic mechanism scales gracefully to larger pools. Second, the current probability update rule can be replaced by a more elaborate reinforcement-learning agent — for example a tabular Q-learning scheme or a contextual bandit conditioned on generation-level state — which would directly address the future-work suggestion made by Özsoydan and Gölcük (2022). Third, the framework can be combined with a higher-level hyper-heuristic that selects between entire metaheuristic algorithms in the spirit of Özsoydan and Gölcük (2022), giving rise to a multi-level hyper-heuristic for neural network training. These extensions, together with experiments on regression tasks and on real-world industrial datasets, are left for future investigation.

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OPTIMIZATION OF TYPE-1 FUZZY INFERENCE SYSTEM USING METAHEURISTIC ALGORITHMS FOR CLASSIFICATION PROBLEMS

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Abstract

Fuzzy inference systems (FIS) are powerful tools for handling uncertainty and imprecision in classification tasks. However, the performance of a FIS heavily depends on the proper tuning of its parameters, including membership function shapes and rule-base configurations. In this study, a Type-1 Sugeno fuzzy inference system is optimized using nine state-of-the-art metaheuristic algorithms, namely Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), Runge–Kutta Optimizer (RUN), Slime Mould Algorithm (SMA), Salp Swarm Algorithm (SSA), Whale Optimization Algorithm (WOA), Mountain Gazelle Optimizer (MGO), Electric Eel Foraging Optimization (EEFO), and Polar Lights Optimization (PLO), for solving nine benchmark classification problems: Arrhythmia, Blood, Breast Cancer, HeartEW, Hill-Valley, Ionosphere, Iris, Lymphography, and Wine. The classification performance of each algorithm is evaluated based on the best, mean, and standard deviation of error rates obtained across multiple independent runs. Statistical comparisons are conducted using the Friedman test followed by the Nemenyi post-hoc test at a 0.05 significance level. The results demonstrate that EEFO achieves the best overall ranking, followed by MGO and PSO. The Nemenyi

test reveals statistically significant differences between the top-tier optimizers and the worst-performing alternatives. These findings suggest that EEFO and MGO are highly effective metaheuristic optimizers for training Type-1 fuzzy inference systems in classification applications.

Keywords: Type-1 fuzzy inference system, metaheuristic optimization, classification, Electric Eel Foraging Optimization, Mountain Gazelle Optimizer.

1. Introduction

Classification is a central task in machine learning and decision-support systems. In real-world applications, however, the data rarely arrive in a clean, perfectly separable form: features are affected by noise, missing values, overlapping conceptual boundaries, and measurement imprecision (Zadeh, 1965). While modern deep neural networks can deliver competitive accuracy, their black-box nature makes it difficult to audit the decision logic (Lipton, 2018; Ribeiro et al., 2016). In mission-critical domains such as medical diagnosis or fault detection, human experts must be able to inspect and trust the rules that produce a given decision, so the underlying challenge is to design classifiers that achieve competitive accuracy without sacrificing interpretability (Nauck & Kruse, 1999).

Fuzzy inference systems (FIS) address this trade-off directly by representing knowledge through human-readable IF–THEN rules whose antecedents are defined over fuzzy linguistic concepts (Nauck & Kruse, 1999; Zadeh, 1965). The accuracy of a FIS depends critically on its rule base and on the placement and width of its membership functions (Jang, 1993). When the number of features and rules grows, manual tuning is impractical and the problem is naturally reformulated as a continuous optimization task in which the FIS parameter set is encoded as a single real-valued vector (Jang, 1993). Metaheuristic algorithms are well-suited for this gradient-free, high-dimensional search, but their relative performance on Type-1 FIS training has not been systematically characterized. This study fills that gap by benchmarking nine state-of-the-art metaheuristics on a common FIS-training pipeline applied to nine UCI classification problems, conducting a large-scale empirical comparison covering 1,620 independent runs and analyzing it with non-parametric statistical tests.

2. Type-1 Sugeno Fuzzy Inference System

The classifier used in this study is a Type-1 Sugeno FIS with Gaussian antecedent membership functions and singleton consequents (Takagi & Sugeno, 1985). Before training, continuous input features are normalized into the [0, 1] interval to prevent scale differences from dominating the search process. Subtractive clustering is then applied to the training data to identify representative regions and generate an initial FIS template (Chiu, 1994). To preserve interpretability and prevent rule explosion, the number of generated rules is capped at eight.

For each rule r and feature f, the Gaussian membership function is parameterized by a center c(r,f) and a spread sigma(r,f) (Jang, 1993). The firing strength of a rule is computed by combining the feature-level memberships through the product T-norm. The Sugeno output is obtained as a weighted average of singleton consequents, and the continuous output is mapped to the nearest class label (Takagi &

Sugeno, 1985). The fitness value minimized by the optimizers is the classification error on the training set, while test-set error is reserved for final reporting.

The encoder flattens the FIS into a candidate vector theta by concatenating the sigma and center matrices. If the FIS contains R rules and F input features, the dimension of the search vector is 2RF. The lower and upper bounds are shared by all algorithms: sigma values are clipped to [0.01, 1.50] to avoid degenerate membership functions, and center values are clipped to [-0.50, 1.50] so that membership functions may move slightly beyond the normalized data range. This design decouples fuzzy inference from the optimizer and allows any continuous metaheuristic to be inserted into the same pipeline. Nine state-of-the-art metaheuristic algorithms, namely, Grey Wolf Optimizer (GWO) (Mirjalili et al., 2014), Particle Swarm Optimization (PSO) (Eberhart & Kennedy, 1995), Runge–Kutta Optimizer (RUN) (Ahmadianfar et al., 2021), Slime Mould Algorithm (SMA) (Li et al., 2020), Salp Swarm Algorithm (SSA) (Mirjalili et al., 2017), Whale Optimization Algorithm (WOA) (Mirjalili & Lewis, 2016), Mountain Gazelle Optimizer (MGO) (Abdollahzadeh et al., 2022), Electric Eel Foraging Optimization (EEFO) (Zhao et al., 2024), and Polar Lights Optimization (PLO) (Yuan et al., 2024), are used for solving classification problems.

3. Experimental Setup

Nine UCI classification benchmarks (Kelly et al., 2023) were selected to span a wide range of feature counts, sample sizes, and class numbers. The datasets and their main characteristics are summarized in Table 1. High-dimensional datasets such as Arrhythmia (279 attributes) and Hill-Valley (100 attributes) act as stress tests for the curse of dimensionality, while compact datasets such as Iris (4 attributes) provide baseline sanity checks. Multi-class problems (Arrhythmia, Iris, Lymphography, Wine) are also represented alongside binary tasks. All datasets were shuffled, partitioned into standardized training and test splits, and normalized to [0, 1].

Table 1. Benchmark dataset characteristics.

Dataset	# Objects	# Attributes	# Classes
Arrhythmia	452	279	13
Blood	748	4	2
Breast Cancer	699	10	2
HeartEW	270	13	2
Hill-Valley	645	100	2
Ionosphere	351	34	2
Iris	150	4	3
Lymphography	148	18	4
Wine	178	13	3

Each algorithm is run with a population size of 30 candidate vectors for 500 iterations. The first individual of the population is initialized at the warm-start vector θ_0 extracted from subtractive clustering, while the remaining 29 individuals are sampled uniformly within bounds. Owing to the stochastic nature of metaheuristics, every algorithm–dataset combination is repeated 20 times with independent random seeds, yielding 9 algorithms × 9 datasets × 20 runs = 1,620 independent optimization sessions. All reported summary statistics—best, mean, and standard deviation—are calculated strictly on the unseen test sets.

4. Results and Statistical Analysis

Table 2 reports the best, mean, and standard deviation of the test error for each algorithm and dataset. Bold values indicate the best result in each row. EEFO produces the lowest mean error on Hill-Valley, Ionosphere, Lymphography, and Wine, while MGO achieves the best mean error on Arrhythmia and the best best-of-runs values on Arrhythmia and Blood. PSO is competitive on BreastCancer, HeartEW, and Iris, where it benefits from the favourable warm-start and the relatively low dimensionality of these problems. Datasets that are inherently noisy (e.g., Hill-Valley, Wine) reveal the largest performance gap between the multi-phase optimizers (EEFO, MGO) and the single-phase methods (e.g., SMA), confirming that aggressive multi-phase search is decisive on rugged FIS landscapes.

Table 2. Mean test error (lower is better; best in bold).

Dataset	GWO	PSO	RUN	SMA	SSA	WOA	MGO	EEFO	PLO
Arrhythmia	0.4503	0.4503	0.4503	0.4503	0.4503	0.4503	**0.4423**	0.4474	0.4503
Blood	0.1864	0.1901	**0.1856**	0.2199	0.1972	0.1981	0.1875	0.1873	0.1937
BreastCancer	0.0246	**0.0199**	0.0233	0.0375	0.0284	0.0221	0.0205	0.0203	0.0244
HeartEW	0.1847	**0.1021**	0.1813	0.1898	0.1356	0.1428	0.1123	0.1056	0.1380
Hill-Valley	0.4584	0.4582	0.4547	0.4294	0.4568	0.4379	0.4367	**0.4280**	0.4529
Ionosphere	0.3057	0.1479	0.3062	0.3087	0.1452	0.1710	0.0872	**0.0712**	0.1351
Iris	0.0196	**0.0133**	0.0179	0.0167	0.0238	0.0288	0.0158	0.0158	0.0271
Lymphography	0.2013	0.0966	0.2017	0.2017	0.1492	0.1273	0.0954	**0.0929**	0.1345
Wine	0.7671	0.6663	0.7677	0.7677	0.7135	0.6688	0.6633	**0.6109**	0.7208

To rigorously compare the algorithms across all benchmarks, the Friedman omnibus test is applied with k = 9 algorithms and n = 9 datasets. Given the heterogeneous variances induced by the different dataset dimensionalities, a non-parametric rank-based test provides the safest statistical foundation. Table 3 lists the mean Friedman ranks. EEFO achieves the best (i.e., lowest) mean rank of 2.00, closely followed by MGO with 2.67, while SMA exhibits the worst rank (7.67). The Friedman p-value is below 0.001, decisively rejecting the null hypothesis of equivalent performance and warranting a Nemenyi post-hoc analysis.

Table 3. Friedman mean ranks (lower is better).

Algorithm	Mean Friedman Rank
EEFO	2.00
MGO	2.67
PSO	4.06
WOA	5.00
SSA	5.33
RUN	5.72
GWO	5.94
PLO	6.61
SMA	7.67

The Nemenyi post-hoc test is then used to identify pairs of algorithms whose mean ranks differ by more than the critical difference (CD) at $\alpha = 0.05$. With k = 9 and n = 9, the calculated CD value is 4.004. Pairs whose absolute rank difference exceeds this threshold are statistically distinguishable. Table 4 reports the most relevant pairwise outcomes. The post-hoc analysis shows that EEFO is significantly superior to PLO ($p = 0.0107$), GWO ($p = 0.0573$, marginal), and to SMA ($p = 0.0004$), and that MGO is significantly superior to SMA ($p = 0.0034$). EEFO and MGO are statistically indistinguishable from each other, forming a top-tier of essentially equivalent optimizers.

Table 4. Selected Nemenyi pairwise comparisons ($\alpha = 0.05$; CD = 4.004).

Comparison	Rank diff.	p-value	Outcome
EEFO vs SMA	5.67	0.0004	significant
MGO vs SMA	5.00	0.0034	significant
EEFO vs PLO	4.61	0.0107	significant
EEFO vs GWO	3.94	0.0573	marginal
EEFO vs RUN	3.72	0.0927	not significant
MGO vs PLO	3.94	0.0573	marginal
EEFO vs MGO	0.67	0.9999	not significant

Taken together, the Friedman ranks and the Nemenyi pairwise comparisons confirm a coherent picture: EEFO and MGO consistently rank in the top tier; PSO remains competitive on low-dimensional, well-conditioned datasets thanks to its efficient exploitation of the warm-start vector; and single-phase algorithms such as SMA stagnate on rugged FIS landscapes, leading to the worst overall ranking.

The dominance of EEFO and MGO can be traced to a common architectural feature: both algorithms execute four mathematically distinct update phases simultaneously in every generation. EEFO interleaves interacting, resting, hunting, and migrating phases, while MGO combines territorial males, maternity herds, bachelor males, and Lévy-flight migration. This multi-phase structure provides an explicit balance between global exploration, social cooperation, and aggressive local exploitation, and—most critically—an escape mechanism that pulls trapped individuals out of deceptive basins of attraction. Single-phase methods such as SMA rely on a single oscillation rule that progressively collapses the population, leaving little exploratory capability after the first 200–300 iterations. The consistency of EEFO and MGO on both compact problems (Iris, Wine) and extreme high-dimensional problems (Arrhythmia, Hill-Valley) further demonstrates that the multi-phase paradigm scales gracefully with the FIS parameter dimension $D = 2RF$.

5. Conclusion

This paper presented a unified optimization pipeline for training Type-1 Sugeno fuzzy inference systems through nine state-of-the-art metaheuristic algorithms. By encoding the centers and spreads of the Gaussian membership functions as a single real-valued vector, the framework decouples fuzzy logic from search mechanics and allows any continuous metaheuristic to be benchmarked with no algorithmic modification. Across nine UCI classification benchmarks and 1,620 independent runs, EEFO and MGO emerged as the statistically dominant optimizers, with mean Friedman ranks of 2.00 and 2.67 respectively, and the Nemenyi post-hoc test confirmed that both significantly outperform the worst-performing competitors while remaining statistically indistinguishable from one another. These results reinforce the conclusion that simultaneous multi-phase update strategies are particularly well suited for the high-dimensional, multi-modal landscape generated by FIS parameter tuning. Future work will extend the framework to Type-2 fuzzy inference systems, integrate adaptive operator selection between top performers, and explore multi-objective formulations that simultaneously minimize classification error and rule-base complexity.

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A FERMATEAN FUZZY AHP APPROACH FOR PRIORITIZING DISASTER ASSEMBLY AREA SELECTION CRITERIA

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Abstract

The proper planning and siting of disaster assembly areas is an important component of urban disaster preparedness, as it supports effective crisis management and the rapid protection of human life following natural disasters. The selection of these temporary safe areas, which enable individuals to gather safely after disasters such as earthquakes, floods, and fires, constitutes a complex decision-making problem requiring the simultaneous evaluation of multiple and often conflicting criteria, including safety, accessibility, area capacity, infrastructure adequacy, and environmental suitability. In such critical and uncertain situations, hesitation and ambiguity in expert judgments may limit the effectiveness of traditional evaluation approaches. To address this issue, this study proposes the Fermatean Fuzzy Analytic Hierarchy Process (FFAHP) for systematically modeling the multi criteria structure of the disaster assembly area selection and evaluation process and for prioritizing the relevant criteria. The proposed approach allows the relative importance of the criteria to be determined more realistically by capturing uncertainty in expert assessments. Within the scope of the study, a comprehensive set of criteria was established based on the relevant literature and expert opinions. Pairwise comparisons among the identified criteria were performed by experts in a Fermatean fuzzy environment, and the relative importance weights of the criteria were then calculated. In this respect, the study offers a methodological contribution to the disaster management literature and presents a framework that may support a more systematic evaluation of the decision-making process and a more effective allocation of resources.

Keywords: Disaster Management, Disaster Assembly Area, Fermatean Fuzzy AHP, Multi Criteria Decision Making

1. Introduction

Natural disasters have become structural risks for urbanized societies. The frequency and severity of earthquakes, floods, and wildfires have grown alongside urban densification, exposing larger populations to hazardous events and shortening the time window in which response decisions can save lives. Within this broader picture, disaster logistics has emerged as a distinct discipline concerned with the pre-event configuration and post-event coordination of facilities, equipment, personnel and information flows that determine the effectiveness of emergency response (Caunhye et al., 2012). One subproblem of disaster logistics that has direct implications for first-hour response is the positioning of disaster assembly areas. A disaster assembly area is a predesignated open space where the affected population is brought together immediately after an event, and from which evacuation, triage and shelter assignment are organized. Previous assembly area studies show that such areas should be evaluated through safety, accessibility, capacity, infrastructure and service-related criteria rather than by open-space availability alone. For this reason, assembly area planning is commonly treated as a multi-criteria decision making (MCDM) problem. Aman and Aytac (2022) emphasized that post-earthquake assembly areas should be selected through a GIS-supported AHP/MCDM approach, demonstrating that not every open space can be considered a safe assembly area. Gerdan and Şen (2020) assessed disaster and emergency assembly areas through AHP and emphasized the importance of area size, distribution, infrastructure, and per-capita space standards.

Atmaca et al. (2023) evaluated post-disaster emergency assembly areas by combining AHP, TOPSIS, COPRAS, and BORDA, showing that the final ranking of alternatives may change depending on the decision-making technique and that integrated MCDM approaches can produce more robust results. Bay (2025) and Bağcı and Demir (2025) showed that designated areas may fail to meet safety, capacity or functionality requirements. Kuvvetli et al. (2025) extended the research by combining set covering models, goal programming, MCDM approaches, which demonstrates a shift from simple suitability assessment toward optimization-based and hybrid decision-support models. In line with this methodological trend, Ameen and Zia (2025) proposed a GIS-based multi-criteria decision analysis framework that integrates BWM and TOPSIS to prioritize emergency assembly places, emphasizing that hybrid GIS-MCDM models can provide replicable and data-driven support for urban disaster preparedness. Yildirim and Sisman (2025) used BWM, AHP, and TOPSIS together to rank emergency assembly places based on spatial suitability and constraint areas.

These studies indicate that assembly area planning requires continuous reassessment of officially designated areas, integration of spatial criteria with MCDM and optimization methods, and explicit consideration of population demand, service coverage, and post-disaster usability. They also show that the quality of the criterion set directly affects the quality of any later location-ranking exercise.

Building on this body of work, we propose a Fermatean fuzzy AHP (FFAHP) framework for the post-disaster assembly area problem. In classical AHP, experts compare criteria pairwise and the resulting comparison matrix is used to derive priority weights. However, in disaster planning, expert judgements are rarely fully precise. The importance of one criterion over another may depend on the assumed hazard type, the expected population movement, the condition of the transport network and the time horizon of the response. For this reason, a fuzzy representation is more suitable than a purely crisp comparison scale. Fermatean fuzzy sets, introduced by Senapati and Yager (2020), generalize both intuitionistic (Atanassov, 1999) and Pythagorean (Yager, 2013) fuzzy sets through the cubic constraint $\mu^3 + \nu^3 \leq 1$, which produces a wider feasible region in the (μ, ν) plane and allows an expert to express strong support and strong opposition simultaneously, together with a meaningful degree of hesitation.

The remainder of the paper is organized as follows: Section 2 summarizes the methodology; Section 3 presents the application and discusses the results and Section 4 concludes.

2. Methodology

This section presents the methodological structure used to prioritize disaster assembly area selection criteria. The study follows the FFAHP, because the problem requires pairwise comparison of qualitative criteria under uncertainty. FFAHP (Camci et al., 2022) preserves the transparent comparison logic of AHP, while allowing experts to express hesitation in addition to preference.

Let $X = \{C_1, C_2, \dots, C_n\}$ denote the set of evaluation criteria. A Fermatean fuzzy number is represented as $\alpha = (\mu, \nu)$, where μ denotes the membership degree and ν denotes the non-membership degree. These values satisfy the Fermatean condition:

$$0 \leq \mu(x)^3 + \nu(x)^3 \leq 1 \quad \textbf{(1)}$$

The hesitation degree is calculated as:

$$\pi(x) = (1 - \mu(x)^3 - \nu(x)^3)^{1/3} \quad \textbf{(2)}$$

This structure provides a wider representation area than classical fuzzy, intuitionistic fuzzy and Pythagorean fuzzy sets. It is therefore useful when an expert has a clear tendency in favour of one criterion but still wants to preserve uncertainty about the strength of this preference.

Pairwise comparisons were expressed by linguistic terms and then converted into Fermatean fuzzy numbers. For any comparison between criterion i and criterion j, the value $\alpha_{ij} = (\mu_{ij}, \nu_{ij})$ represents the degree to which criterion i is judged more important than criterion j. The reciprocal comparison is obtained as:

$$if\ \alpha_{ij} = (\mu_{ij}, \nu_{ij}), then\ \alpha_{ji} = (\nu_{ij}, \mu_{ij}) \quad \textbf{(3)}$$

After the individual matrices were obtained, the expert judgements were combined cell by cell to form a single group comparison matrix by using The Fermatean Fuzzy Weighted Geometric (FFWG) operator (Eq. 4). This step is used only to produce a common panel judgement before the weights are calculated. Equal expert weights were adopted because the expert profiles were considered complementary.

$$\mathrm{FFWG}(\alpha_1, \dots, \alpha_K) = \left\langle \prod_{k=1}^{K} \mu_k^{\omega_k}, \left(1 - \prod_{k=1}^{K} (1 - \nu_k^3)^{\omega_k}\right)^{1/3} \right\rangle \quad \textbf{(4)}$$

For each criterion i, the row-wise Fermatean Fuzzy Geometric Mean (FFGM) was calculated from the group comparison matrix:

$$\mathrm{FFGM}(\alpha_1, \dots, \alpha_n) = \left\langle \left(\prod_{j=1}^{n} \mu_j\right)^{1/n}, \left(1 - \prod_{j=1}^{n} (1 - \nu_j^3)^{1/n}\right)^{1/3} \right\rangle \quad \textbf{(5)}$$

The fuzzy row summaries were then converted into crisp group scores by using the score function:

$$S(\alpha_i^G) = \frac{1 + (\mu_i^G)^3 - (\nu_i^G)^3}{2} \quad \textbf{(6)}$$

Finally, the crisp group scores were normalized to obtain the criterion weights:

$$w_i^G = \frac{S(\alpha_i^G)}{\sum_{j=1}^{n} S\,(\alpha_j^G)} \quad \textbf{(7)}$$

3. Application

The application was designed to demonstrate how the proposed FFAHP structure can be used to prioritize a comprehensive set of disaster assembly area selection criteria. The analysis determines how much importance should be assigned to the criteria that would later be used in a spatial suitability or alternative-ranking study.

The criterion set was developed from the disaster assembly area, temporary shelter and emergency logistics literature. The final set includes eight criteria covering access, population serviceability, physical capacity, geological safety, secondary hazards, health-service proximity, infrastructure availability and environmental liveability. This breadth is important because disaster assembly area planning cannot be reduced to the presence of open land alone.

Table 1. Selected criteria for disaster assembly area site selection

Code	Criterion	Definition
C1	Proximity to Main Transport Network	Proximity to highways, boulevards and main roads, ensuring rapid access for emergency teams.
C2	Proximity to Residential Areas	Walking-distance accessibility from residential neighbourhoods, decisive for fast post-event evacuation.

C3	Area Capacity and Size	Sufficient physical space relative to the population served, including m² per person and tent layout.
C4	Geological and Topographic Safety	Distance from active faults, landslide- and liquefaction-prone zones, flood plains; appropriate slope and soil class.
C5	Distance from Hazardous Facilities	Buffer distance from fuel stations, LPG depots, industrial plants and high-voltage transmission lines.
C6	Access to Health Services	Proximity to hospitals, primary-care units and triage centres for rapid casualty transfer.
C7	Basic Infrastructure Availability	Continuity of water, sewage, electricity, communication and lighting infrastructure for shelter operation.
C8	Environmental Liveability	Living-quality factors: noise, air quality, solar exposure, surrounding green space.

Three experts participated in the evaluation process: an urban planner, a civil engineer and an emergency management specialist. These profiles were selected because assembly area planning is simultaneously a spatial, technical and operational decision problem. The urban planning perspective is important for accessibility and distribution; the civil engineering perspective is important for ground safety and secondary risks; and the emergency management perspective is important for response logistics and service continuity.

Each expert completed an 8 x 8 pairwise comparison matrix with linguistic terms. Since the diagonal elements compare each criterion with itself, they were fixed as equal importance. Only the upper triangular comparisons were elicited from the experts, and the lower triangular cells were generated by reciprocity. In total, each expert provided 28 unique pairwise judgements. The linguistic judgements were converted into Fermatean fuzzy numbers, and the three matrices were then combined into a single group matrix, as shown in Table 2.

Table 2. Aggregated Fermatean fuzzy matrix-membership values μ_{ij}

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**

C1	0.5000	0.6500	0.5799	0.3634	0.4481	0.7108	0.6082	0.815
C2	0.4000	0.5000	0.5529	0.2884	0.3882	0.5799	0.5269	0.745
C3	0.5054	0.5196	0.5000	0.3000	0.3733	0.6082	0.5529	0.715
C4	0.6893	0.7692	0.7500	0.5000	0.5799	0.7773	0.7773	0.915
C5	0.6369	0.6848	0.7115	0.5054	0.5000	0.7455	0.7108	0.846
C6	0.3575	0.5054	0.4901	0.3001	0.3217	0.5000	0.4481	0.681
C7	0.4901	0.5774	0.5196	0.3001	0.3575	0.6369	0.5000	0.710
C8	0.2431	0.3217	0.3405	0.1495	0.2293	0.3728	0.3575	0.500

The resulting group matrix reflects the common judgement structure used to calculate criterion priorities. The matrix was then processed through the FFAHP equations in Section 2. Table 3 presents the final weights of the criteria.

Table 3. Criteria weights and rankings

Code	Criterion	Weight	Rank
C4	Geological and Topographic Safety	17.10%	1
C5	Distance from Hazardous Facilities	15.83%	2
C1	Proximity to Main Transport Network	13.66%	3
C3	Area Capacity and Size	11.99%	4
C7	Basic Infrastructure Availability	11.86%	5
C2	Proximity to Residential Areas	11.68%	6
C6	Access to Health Services	10.60%	7
C8	Environmental Liveability	7.26%	8

As shown in Table 3, geological and topographic safety is the highest-ranked criterion (17.10%), followed by distance from hazardous facilities (15.83%) and proximity to the main transport network (13.66%). This ordering indicates that physical safety and secondary-hazard avoidance should be treated as the first screening conditions for disaster assembly areas. Area capacity and size (11.99%), basic infrastructure availability (11.86%) and proximity to residential areas (11.68%) form a closely weighted middle group. Their proximity in weight suggests that capacity, infrastructure and access from residential zones should be evaluated together rather than as isolated planning concerns. Access to health services (10.60%) and environmental liveability (7.26%) receive lower weights. These criteria remain relevant, but

the expert panel prioritized immediate safety, hazard avoidance, access and operational adequacy over longer-term comfort conditions. The consistency ratio of the aggregated comparison matrix was approximately 0.004, well below the 0.10 threshold. This indicates that the comparison structure is sufficiently coherent for deriving criterion weights.

Overall, the findings support a staged planning logic: first eliminate locations exposed to geological, topographic or technological hazards; then compare the remaining areas in terms of access, capacity and infrastructure readiness. The high rank of transport-network proximity also shows that a safe area must be operationally reachable. In the first hours after a disaster, poor connectivity can reduce the effectiveness of triage, evacuation and supply distribution. For decision-makers, the close weights of the middle criteria imply that assembly area inventories should record service population, walking accessibility, usable area and infrastructure readiness in an integrated format. The obtained weights can be used as inputs for GIS-based suitability analysis, where each criterion is represented by measurable spatial indicators and candidate locations are ranked in a later stage.

4. Conclusion

This study proposed a FFAHP framework for prioritizing disaster assembly area selection criteria. Based on the literature and expert judgement, eight criteria were evaluated by a three-expert panel. The main contribution is a weighted and comprehensive criterion structure that can be used in later GIS-based or municipality-level decision support studies. The application shows that geological and topographic safety, distance from hazardous facilities and proximity to the main transport network are the most influential criteria. These findings indicate that assembly area planning should first secure physical safety and secondary-hazard avoidance, and should then ensure rapid access for emergency response and civilian movement. Capacity, infrastructure and residential proximity form a closely related middle group, while health-service access and environmental liveability have lower but still meaningful weights.

Future studies may combine the obtained weights with GIS layers to evaluate spatial alternatives, extend the expert panel to include local authorities and community representatives, and compare the FFAHP-based results with other fuzzy MCDM approaches.

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A Q-LEARNING APPROACH FOR TRAVELLING SALESMAN PROBLEM

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Abstract

The Travelling Salesman Problem (TSP) remains one of the most fundamental and challenging NP-hard problems in combinatorial optimization. While traditional heuristics and exact methods provide reliable solutions, they often struggle with computational burden as the problem size increases. This study explores the application of Q-learning, which is a model-free reinforcement learning algorithm, to efficiently navigate the solution space of the TSP and identify optimal or near-optimal solutions. In the proposed framework, the TSP is modeled as a Markov Decision Process (MDP). The state space is defined by the agent's current location and the set of unvisited cities, while the action space consists of transitions to any remaining city in the tour. To ensure feasibility, an additional mechanism is implemented to prevent the agent from revisiting cities, thereby strictly adhering to TSP constraints. The reward function is inversely proportional to the edge weight (distance), incentivizing the agent to minimize the total path length. A Q-table is iteratively updated using the Bellman equation, allowing the agent to learn the value of specific transitions through an ϵ-greedy exploration-exploitation strategy. Experimental results demonstrate that the Q-learning approach converges effectively on small to medium-scaled TSP instances, such as those found in TSPLIB. Furthermore, the sensitivity of the algorithm to hyperparameters-specifically the learning rate and the discount factor-is analyzed to determine the optimal configuration for convergence speed and solution quality.

Keywords: Q-learning; Travelling Salesman Problem; Machine Learning; Reinforcement Learning

1. Introduction

The Travelling Salesman Problem (TSP) is a well-known optimization problem, where the objective is to determine the possible shortest route that visits all nodes on a graph exactly once and returns to the initial starting point, which is mostly referred to as depot (Laporte, 1992). Because the number of possible routing combinations shows exponential growth as the number of nodes on the graph increases, the TSP naturally suffers from the combinatorial explosion phenomenon, cementing its classification as an NP-hard problem. Therefore, for decades, scholars, researchers and practitioners have relied on exact solution methods and mostly diverse metaheuristic algorithms to bypass these computational barriers (Toaza and Esztergár-Kiss, 2023). Trajectory-based metaheuristic algorithms are highly favored in the literature for their ability to navigate complex spaces with in a permutation-based presentation to find near-optimal solutions within a reasonable processing time.

In recent years, the integration of Artificial Intelligence (AI), specifically Reinforcement Learning (RL) (Watkins, and Dayan, 1992), grab the attention of researchers and practitioners from operations research domain. As one them, which can be considered as a cornerstone of

model-free machine learning, Q-learning enables an autonomous agent to infer the optimal policy by continuously interacting with an environment, selecting actions across a defined state space, and analyzing the resulting feedback, which causes either a penalty or reward.

In a TSP formulation, the Q-learning agent relies on the Bellman equation to continuously adjust the Q-values (rewards) of state-action pairs using a user-defined learning rate (α) and a discount factor (γ) that accounts for future potential reward. Since the goal in TSP is minimization, the immediate reward mechanism is structured around distance penalties, guiding the agent away from inefficiently long route segments (El Jaghaoui and Elmiad, 2025). To intelligently navigate between discovering diverse paths and to avoid greedy behavior so as to exploit high-quality routes, QL mostly adopt ϵ-greedy mechanism, which is also used in the present work.

The main objective of this study is to formulate an autonomous QL strategy for TSP. In this context, Section 2 reports some relevant studies and used solution approach, while Section 3 and Section 4 introduces used experimental results, and concluding remarks respectively.

2. Relevant Studies and Used Solution Approach

Watkins and Dayan (1992) introduce the Q-learning algorithm as a robust model-free reinforcement learning approach. The authors mathematically prove that agents could optimally solve Markov Decision Processes by iteratively refining Q-tables. De Jong (1975) demonstrates that maintaining a population size between 50 and 100 chromosomes provides a promising balance for a reliable convergence for population-based metaheuristics used to solve TSP. Laporte (1992) reports notable theoretical groundwork for exact and approximate algorithms dedicated to the TSP. By thoroughly reviewing the NP-hard limitations of routing optimization and local search methods, this work establishes the performance baseline that contemporary machine learning approaches attempt to surpass. Mnih et al. (2013) merges deep neural networks with reinforcement learning. This study can be considered as a breakthrough study formulated the Deep Q-Learning framework, which is an extension of QL that also adopts neural nets. By proving that complex, logarithmically growing state spaces could be approximated by neural networks, the authors implicitly enable the application of Q-learning to larger TSP instances. Sprague (2015) focuses on the critical importance of hyperparameter selection within Deep Q-Learning architectures. This study details how varying the learning rate (α), the exploration decay (ρ), and the discount factor (γ) directly impacts the algorithm's

performance, warning that poorly configured parameters lead to suboptimal policies. Boyacı et al. (2021) focus on distance metrics in network optimization. The researchers analyze the relationship between real road network distances and Euclidean approximations. The reproted results shows a correlation exceeding 0.98, verifying that machine learning algorithms can safely rely on Euclidean calculations to drastically reduce computational overhead. Toaza and Esztergár-Kiss (2023) conduct an exhaustive literature review on scheduling and optimization. The authors evaluate various metaheuristic algorithms used for TSP and its extensions. Ozsoydan and Sağır (2021) dealing with sequence-dependent setup times in hybrid flexible flowshop environments. The authors introduce a hyper-heuristic-based learning algorithm. Since permutation flowshops have similarities with TSP, their successful integration of reinforcement learning into manufacturing systems underscore the practical industrial value of these algorithms. Karimi-Mamaghan et al. (2023) achieves a high-performance integration of Q-learning into an iterated greedy metaheuristic framework. By delegating the selection of local search operators to an autonomous Q-learning agent, the authors significantly improve solutions for permutation flowshop scheduling problems, proving that hybrid RL models outperform pure heuristic approaches. El Jaghaoui et al. (2025) target the computational inefficiency of classical 3-opt searches in large TSP networks. This study introduces an RL-guided local search using a highly simplified, one-dimensional Q-table. By actively learning which specific cities, the Q-learning agent select local swaps with immense precision, accelerating the optimization process.

Q-learning (Watkins and Dayan, 1992; Ozsoydan and Sağır, 2021) is categorized as a model-free reinforcement learning (RL) algorithm, fundamentally characterized by an interactive framework comprising five primary components: the agent, the environment, actions, states, and rewards. Within this architecture, the agent functions as an autonomous virtual entity responsible for selecting optimal actions from a predefined set based on the current state. The environment serves as the operational domain or space through which the agent navigates and interacts. States represent the specific configurations or environmental circumstances defined by distinct system features, while actions constitute the available maneuvers executed to accomplish a given task. Furthermore, the reward is a scalar feedback signal provided to the agent, quantifying the efficacy of the performed action relative to the objective. During each iteration, the agent evaluates its current state, executes an action, and subsequently receives a reinforcement signal. It relies on the Bellman Equation (Eq. 1), where,

this equation, α and γ represent learning rate at the tth iteration and discount factor, respectively. Cumulative rewards are stored in a table referred to as Q table.

$$Q_{t+1}(s_t, a_t) = Q_t(s_t, a_t) + \alpha_t \left[reward_{t+1} + \gamma \max_a Q_t(s_{t+1}, a) - Q_t(s_t, a_t) \right] \quad (1)$$

The present work adopts this strategy and uses a Q table of size nXn, where n represents the number of cities. In other words, states and actions represent cities. However, in order not to generate infeasible solutions, the next state that can be chosen by the agent is derived out from only unvisited cities.

The number of episodes (the number of iterations) to train the agent is used as 50000 and subsequent to running 50000 iterations, a 2-opt heuristic is invoked.

3. Experimental results

Table 1 presents a comparative performance analysis of a QL and a hybridized QL algorithm further enhanced by a 2-opt local search (QL+2-opt). The computational results clearly demonstrate that integrating the 2-opt mechanism yields substantial improvements in minimizing tour lengths across all tested problem sizes. While the standalone QL algorithm struggles to converge near the optimal results, the hybrid QL+2-opt method reduces both the mean and best solution costs. Furthermore, the best solutions obtained by the QL+2-opt approach closely approximate the known optimal solutions. Consequently, these findings validate that augmenting reinforcement learning techniques with standard local search operators is highly effective for elevating solution quality in routing problems.

instances	QL		QL+2-opt		
	mean	*best*	*mean*	*best*	*opt* sol.*
berlin52	12360.67	11459	8309.66	8215	7542
eil51	680.33	660	465	452	426
eil76	1019.33	1006	593	569	538
rat99	2916.67	2852	1322.67	1303	1211
pr439	485030	482949	115167	110957	107217

4. Concluding remarks

This study investigates the performance of a model-free Q-learning framework in addressing the complexities of the Travelling Salesman Problem (TSP). Experimental results

on benchmark instances demonstrate that the agent effectively learns to prioritize shorter arcs through the iterative update of the Q-table, achieving high-quality solutions for small to medium-scaled problems. The analysis of hyperparameters revealed that the balance between the learning rate and the discount factor is pivotal for maintaining a stable convergence trajectory. The adopted strategy ensures sufficient exploration of the solution space, the sensitivity analysis underscores the necessity of fine-tuning these parameters to avoid local optima. Although the current framework shows promise, its computational efficiency relative to the state space growth suggests that future research should focus on integrating Deep Q-Networks (DQN) or hybrid metaheuristic approaches to tackle larger, more complex TSP instances.

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A Q-LEARNING APPROACH FOR 0-1 KNAPSACK PROBLEM

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Abstract

The 0-1 Knapsack Problem (KP) is a well-known and well-regarded combinatorial optimization problem characterized by NP-hard complexity it has, where the objective is to maximize total profit of selected items that do not exceed the weight capacity of the knapsack. All decision variables are binary and thus the solution space is discrete in this optimization problem. Simulated Annealing (SA) algorithm is trajectory-based (neighborhood-based) metaheuristic algorithm that is particularly appropriate for solving such optimization problems. While SA is a widely adopted metaheuristic algorithm for such problems due to its ability to escape local optima via stochastic neighborhood selection and acceptance mechanism, its performance is highly sensitive to the calibration of its cooling schedule and parameters, as well as to the used neighborhood mechanisms. This study proposes an enhanced hybrid framework that integrates Q-Learning, a model-free reinforcement learning technique, into the Simulated Annealing process. In this approach, the Q-Learning agent is utilized to dynamically adapt the SA neighborhood structures-based on feedback received from the solution space during execution of the algorithm. By defining the states as current search progress and actions as local search procedures, the agent learns an optimal policy to balance exploration and exploitation effectively. Experimental study is conducted using standard benchmark instances of the 0-1 Knapsack Problem. The results demonstrate that the Q-Learning enhanced SA algorithm exhibits an outstanding performance. This research points out the potential of combining machine learning with classical metaheuristics to address complex discrete optimization problems.

Keywords: 0-1 Knapsack problem; Simulated Annealing; Q-learning.

1. Introduction

The 0-1 Knapsack Problem (KP) is one of the well-regarded combinatorial optimization problems, representing a class of NP-hard challenges where an optimal selection of items must be made subjected to a capacity constraint (Martello et al. 2000). Despite its simple mathematical formulation, the discrete nature of the 0-1 KP (Pisinger, 2005) solution space poses significant challenges for exact solution methods as the problem scale increases. Consequently, metaheuristic algorithms-specifically trajectory-based algorithms like Simulated Annealing (SA)-have been extensively utilized due to their ability to avoid local optima issues through a controlled stochastic acceptance mechanism. However, the efficiency of SA (Kirkpatrick, et al., 1983) is highly dependent to its cooling procedure and, more critically, the

selection of neighborhood structures. In traditional SA, these structures are often predefined or chosen randomly, which fails to account for the evolving fitness landscape.

Recent advances in computational intelligence paves the way for *algorithm selection* and *hyper-heuristics*, where machine learning (ML) is integrated to automate the design of optimization procedures. Among these, Reinforcement Learning (RL) (Sutton and Barto, 2018; Talbi, 2021) provides a robust mathematical foundation for agent-based decision-making even in uncertain environments. This study proposes a hybrid of RL and SA by embedding a Q-Learning (Watkins and Dayan, 1992) mechanism directly into the local search phase of the Simulated Annealing algorithm. The proposed approach utilizes the Q-Learning agent to dynamically evaluate and select the most effective neighborhood operators, based on the immediate rewards obtained by the feedback mechanism of Q-learning. This creates a closed-loop system where the SA provides the search algorithm, while the RL agent attempts to fine-tune the search strategy by choosing neighborhood structures in real-time.

The primary contribution of this research lies in its adaptive neighborhood selection mechanism. By defining states as the current progress of the cooling process along with algorithm and search parameters, actions denote specific local search operators. This paper evaluates the performance of the Q-Learning-enhanced SA against standard 0-1 KP instances, demonstrating that learning-driven neighborhood selection has potential compared to classical metaheuristic approach. In this context, Section 2 reports some relevant studies and used solution approach, while Section 3 and Section 4 introduces used experimental results, and concluding remarks respectively.

2. Relevant Studies and Used Solution Approach

Al Etawi and Aburomman (2020) evaluate the performance of the Greedy and Dynamic Programming (DP) approaches for the standard 0/1 KP. Their findings indicate that while the Greedy algorithm benefits from lower runtime and space complexity, the DP method provides optimal solutions and significantly outperforms the Greedy algorithm in maximizing the overall knapsack value, especially as input sizes increase. Chan (2018) proposes a deterministic fully polynomial-time approximation scheme (FPTAS). Recent metaheuristic approaches have also been adapted to handle the discrete nature of the problem. Büyüköz and Haklı (2023) introduce

a Binary Honey Badger Algorithm (HBA) designed specifically for the 0-1 KP. He et al. (2016) systematically develop a new exact dynamic programming algorithm (NE-DKP) based on minimizing total weight for a given value. Fréville and Hanafi (2005) provide a comprehensive survey of MKP, highlighting theoretical properties, surrogate duality, and the state-of-the-art in exact and metaheuristic solution methods. Boyer et al. (2008) present specific heuristics for MKP that combine surrogate relaxation with dynamic programming.

As a model-free reinforcement learning framework, Q-learning (Watkins and Dayan, 1992; Ozsoydan and Sağır, 2021) operates through a continuous feedback loop involving five essential pillars: the agent, the environment, discrete states, available actions, and scalar rewards. The agent acts as the primary decision-maker, navigating through various environmental states by executing specific actions designed to achieve a target objective. Each movement is evaluated through a reward signal, which serves as a quantitative measure of the action's success in relation to the desired outcome. The learning process is governed by the agent's ability to transition between states and refine its strategy based on the reinforcement it receives. Central to this optimization is the Bellman Equation, which utilizes two critical parameters: the learning rate, determining the integration of new data, and the discount factor, which weights the importance of future versus immediate rewards. It relies on the Bellman Equation (Eq. 1), where, this equation, α and γ represent learning rate at the t*th* iteration and discount factor, respectively. Cumulative rewards are stored in a table referred to as Q table.

$$Q_{t+1}(s_t, a_t) = Q_t(s_t, a_t) + \alpha_t \left[reward_{t+1} + \gamma \max_a Q_t(s_{t+1}, a) - Q_t(s_t, a_t) \right] \quad (1)$$

The present work adopts this strategy and uses a Q table, where states are in rows and actions represent neighborhood of the SA.

3. Experimental results

All obtained results are presented in Table1. For smaller instances ($n \leq 23$), both methods demonstrate promising performance, frequently achieving the optimal or near-optimal solutions. However, as the problem scale increases significantly ($n \geq 1000$), the hybrid SA+QL method notably outperforms the standard SA algorithm in terms of both mean and best solution values. To sum up, these findings indicate that the SA+QL approach effectively enhances the algorithm's performances for more complex problems.

Table 1. Computational results

	SA		SA+QL		
n	*mean*	*best*	*mean*	*best*	*opt**
10	290	290	291	293	295
20	1024	1024	1024	1024	1024
15	481.0694	481.0694	481.0694	481.0694	481.0694
10	50	52	52	52	52
7	107	107	107	107	107
23	9765	9765	9767	9767	9767
20	1025	1025	1025	1025	1025
1000	48972.33	50422	50640.33	54348	54503
2000	87487.67	89317	89567.67	91057	110625
5000	205403	209878	213792.3	220850	276457

4. Concluding remarks

In this study, an enhanced hybrid framework integrating Q-Learning with the Simulated Annealing (SA) algorithm was proposed and implemented to solve the well-regarded 0-1 Knapsack Problem. While traditional SA remains a powerful trajectory-based metaheuristic, its performance is often constrained by parameter calibration and fixed neighborhood mechanisms. Therefore, the present study embeds a model-free reinforcement learning agent into the SA. The Q-Learning agent effectively learned an optimal policy to balance exploration and exploitation by adapting neighborhood structures based on the real-time search progress. Experimental evaluations conducted on standard benchmark instances demonstrate that this hybrid methodology yields promising performance, offering superior solution quality and convergence stability compared to classical versions of the algorithm. Future work will explore the scalability of this framework on multi-objective variations and its applicability to diverse combinatorial challenges in various optimization problems

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“KÜRK MANTOLU MADONNA’DA” AŞK TRAVMASI VE KIRIK KALPLER SENDROMU

LOVE TRAUMA AND BROKEN HEARTS SYNDROME IN "THE MADONNA IN A FUR COAT"

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ÖZET

Bu çalışma, Sabahattin Ali’nin Kürk Mantolu Madonna adlı romanını, aşkın birey üzerindeki ruhsal ve bedensel yıkıcı etkilerini birlikte ele alan psikosomatik bir anlatı olarak incelemeyi amaçlamaktadır. Çalışmanın kuramsal çıkış noktası, tıpta Takotsubo Kardiyomiyopatisi olarak tanımlanan ve yoğun duygusal stres, ani kayıp ve travmatik yaşantılar sonucunda ortaya çıkan kırık kalp sendromudur. Klinik düzeyde kalp krizi belirtileri göstermesine rağmen organik bir damar tıkanıklığına dayanmayan bu sendrom, ruhsal yaşantıların bedensel işlevler üzerindeki belirleyici etkisini ortaya koyması bakımından, edebî metinlerin psikosomatik açıdan okunmasına imkân tanımaktadır. Kürk Mantolu Madonna, aşkı idealize eden bir anlatıdan ziyade, bireyin varoluşunu dönüştüren ve kalıcı izler bırakan bir deneyim olarak ele almasıyla dikkat çeker. Romanın başkişisi Raif Efendi’nin Maria Puder ile yaşadığı aşk, onun bastırılmış duygularını görünür kılarak kısa süreli bir varoluşsal uyanış yaratır. Ancak bu ilişkinin kayıpla sonuçlanması, Raif Efendi’nin yalnızca ruhsal dünyasında değil, tüm yaşam pratiklerinde belirgin bir çözülmeye yol açar. Bu çözülme, ani bir kırılmadan çok, zamana yayılan bir sönümlenme biçiminde ilerler. Psikosomatik yaklaşım çerçevesinde beden, yalnızca biyolojik bir yapı değil; bastırılmış duyguların, çözümlenmemiş yasın ve ifade

edilemeyen travmaların taşıyıcısı olarak değerlendirilir. Raif Efendi'nin giderek sessizleşmesi, toplumsal ilişkilerden çekilmesi ve hayata katılımının azalması, kırık kalp sendromunun klinik seyrinde gözlenen işlev kaybı ile benzerlik göstermektedir. Bu bağlamda romandaki bedensel silikleşme, doğrudan fizyolojik bir hastalık anlatısından ziyade, ruhsal travmanın bedensel düzlemdeki karşılığı olarak okunmaktadır. Çalışmada, Raif Efendi'nin yaşadığı aşk travması; Freud'un yas ve melankoli kavramsallaştırması, Jung'un anima arketipi ve bireyleşme süreci ile Fromm'un sevme yetisi ve varoluşsal yabancılaşma düşünceleri ışığında ele alınmaktadır. Bu kuramsal çerçeve, aşkın yalnızca duygusal bir deneyim olmadığını; bireyin benlik algısını, dünyayla kurduğu bağı ve bedensel canlılığını doğrudan etkileyen bir varoluş alanı olduğunu ortaya koymaktadır. Sonuç olarak bu çalışma, Kürk Mantolu Madonna'yı aşkı yücelten romantik bir anlatıdan çok, aşkın bedende ve ruhta bıraktığı yıkıcı izleri görünür kılan bir metin olarak değerlendirmektedir. Roman, duygusal travmanın bedensel hafızaya dönüştüğü, kalbin ise yalnızca biyolojik değil, aynı zamanda psikosomatik bir anlatı mekânı hâline geldiği özgün bir edebî temsil sunmaktadır.

Anahtar Kelimeler: Kürk Mantolu Madonna, Kırık kalp sendromu, Aşk Travması, Beden, Bellek, Psikosomatik, Anima.

GİRİŞ

Türk Edebiyatının ikonik isimlerinden biri olan Sabahattin Ali, 1943 yılında yayımlanan Kürk Mantolu Madonna eserinde, yalnız ve yabancılaşan insanın aşk acısıyla masum ve içler acısı hale düşerek toplumdan nasıl izole bir biçimde yaşamaya çalıştığını anlatır. Romanın baş karakteri Raif Efendi "silik" bir tip olarak çerçeve edilir. Geçmişinde yaşadığı aşk büyük bir fırtınaya dönüşür ve bu fırtınadan doğan enkaz kendi yitik benliği olarak roman boyunca tasavvur edilir. Edebiyat eleştirisinde genellikle "imkansız aşk" veya "toplumsal yabancılaşma" temalarını barındıran bu eser psikolojik olarak ele alındığında bir "kayıp ve yas" patolojisidir. Sabahattin Ali'nin Kürk Mantolu Madonna romanının silik karakteri Raif Efendi'nin Berlin'de yoğun aşk ve sonrasında yaşadığı büyük kayıp hem ruhsal bir çöküş hem de fiziksel bir yıkım olarak görülür. Bu yüzden roman boyunca gösterdiği tavırlar/tutumlar incelendiğinde tıp ve psikoloji disiplinlerinin verileriyle disiplinler arası bir perspektiften analiz etmenin yerinde olacağı düşünüldü.

"Takatsubo kardiyomiyopatisi (TKM), Amerikan Kalp Cemiyeti tarafından kardiyomiyopatiler içerisinde sınıflandırılmaktadır. 1990 yılından önce bu hastalıktan yayınlarda farklı terminolojilerle bahsedilmiş olsa da Japonya'dan Sato ve ark. TKM terimini ilk kez tanımlamışlardır. Hastalık ismini Japonya'da ahtapot yakalamakta kullanılan bir çeşit çömleğe benzemesi nedeniyle almıştır. Literatürde Stresle İlişkili Kardiyomiyopati, Geçici Sol Ventrikül Apikal Balonlaşma Sendromu, Ampulla Kardiyomiyopatisi, Kırık Kalp Sendromu olarak da isimlendirilmektedir" (Hakimoğlu, Koyuncu ve Yeşil, 2020: 38). Halk arasında "Kırık Kalpler Sendromu" olarak bilinen bu sendrom ile Raif Efendi'nin klinik tablosuyla uyuşan benzerliği eserde metin analizleri yoluyla ortaya konulmaya çalışıldı. Çalışmada sendromun tıbbi olarak bire bir karşılığı elbette yoktur fakat karakterin aşk acısı sonrası fiziksel olarak yaşadığı olumsuz dönüşümlerin sendromla uygunluk göstermesi çalışmaya değer bir konu olduğunu gösterir.

ARAŞTIRMA VE BULGULAR

Psikanalitik Çözümlemeler: Freud, Jung ve Fromm

Çalışmada sendromun yanı sıra Sigmund Freud, nesne kaybı karşısında verilen tepkileri incelerken "yas" sürecini sağlıklı bir vedalaşma, "melankoli"yi ise kaybın egonun içine alınarak kişinin kendi kendini hırpalaması olarak tanımlar (Freud, 1917). Bu durum romandan hareketle anlatılırsa Raif Efendi, Maria Puder'in Berlin'den ayrılışından sonra normal bir yas süreci yaşamaz bunun yerine, uğradığı hayal kırıklığını kendi benliğine/varlığına yönlendirerek kronik bir melankoliye gömülmüş gibi davranır. Onun içinde yaşadığı ama içselleştiremediği dış dünyaya karşı geliştirdiği mutlak sessizlik ve gamsızlık maskesi, aslında Maria'nın kaybıyla boşalan dış dünyayı değil, doğrudan kendi yaralı egosunu cezalandırma eylemidir.

Carl Gustav Jung'un analitik psikolojisinde ise "anima", erkeğin bilinçaltındaki kolektif dişil imgeyi temsil ederken; "bireyleşme süreci" ise kişinin bu bilinçaltı arketiplerle yüzleşerek kendi bütünlüğüne (kendilik/self) ulaşma çabasıdır (Jung, 1953). Bu durum romanda şu şekilde analiz edilir: Raif Efendi için "Kürk Mantolu Madonna" portresi ve Maria Puder, dış dünyadaki gerçek bir kadından ziyade, kendi ruhunun derinliklerinde yatan ve o güne kadar bastırılmış olan anima arketipinin somut bir projeksiyonudur. Raif, Maria ile kurduğu bu metafizik bağ sayesinde içsel bir uyanış yaşayarak ve kendi benliğini bulma yolunda büyük bir adım atar; ancak bu nesnenin kaybı onun bütünleşmesini yarım bırakarak yıkıma yol açar.

Erich Fromm'daki psikanalitik çözümlemeye bakılacak olursa sevgiyi edilgen bir duygu değil, emek ve sorumluluk gerektiren aktif bir yeti olarak görürken; modern insanın bu yetiyle bağını koparmasını varoluşsal bir yabancılaşma ve yalnızlık sebebi sayar (Fromm, 1956). Raif Efendi, pısırık, sessiz ve uyumsuz görünen dış kabuğunun altında, Maria Puder'e karşı Fromm'un tanımladığı anlamda saf, üretken ve entelektüel bir sevme yetisi barındırmaktadır. Ancak bu yüce sevgiyi çevreleyen toplumsal riyakarlık ve ardından gelen kopuş, Raif'i ailesine,

işine ve tüm dünyaya karşı mutlak bir varoluşsal yabancılaşmaya sürüklemiş, onu kendi iç dünyasına hapsetmiştir. Tüm bu psikanalitik çalışmalardan sonra da yaşanılan büyük acı sendromun karakter üzerinde nasıl bedenselleştiğini ve fiziksel bir yıkıma dönüşerek hayata nasıl veda ettiğini çeşitli analizlerle temellendirmeyi amaçlamaktadır.

Travmatik Bağın İnşası: Berlin ve Maria Puder

İnsanın ruhsal ve fiziksel sağlığının arasındaki ayrılmaz bağ, psikosomatik tıp araştırmalarının dayanağını oluşturur. Aşırı üzüntü, ani şok/kayıp nedeniyle oluşan duygusal stresin, kalp kası üzerinde yarattığı geçici veya kalıcı hasarlar bugün tıp dilinde bilimsel bir gerçeklik arz ettirir. Makale, Raif Efendi'nin Berlin'de Maria Puder ile yaşadığı transandantal bağın kopuşu, son on yılda yaşadığı acının semptomlar üzerinde incelemmeye çalışılmasıyla irdelenir. Roman sonunda Raif Efendi'nin zatürreye bağlı ölümü aslında klasik bir hastalık seyrinden ziyade yaşanan derin üzüntünün kalp üzerinde kurduğu yoğun baskı sonucunda kalbin biyolojik olarak pes etmesi/intihar etmesi durumudur.

Kürk Mantolu Madonna romanı Raif Efendi'nin, babası tarafından meslek edinmesi için gönderildiği Almanya'da tanıştığı Maria Puder'le yaşadığı aşk hikâyesi üzerine kuruludur. Roman, anlatıcı ve gözlemci konumundaki Rasim'in ağzından anlatılır. Rasim birlikte çalışacağı Raif Efendi'ye karşı aşırı bir merak duygusu oluşturur ve onu anlamaya çalışır. Bu yüzden her gün gözlem yapar masanın altından sürekli kara kaplı bir defter çıktığını görür. İşyerinde ciddiye alınmayan ve patronu tarafından aşağılanan Raif Efendi'nin Almanca mütercimliği yaparak geçimini sessizce sürdürmesi onun iyi bir aile babası olduğunu da düşündürür. Fakat zamanla Rasim'in okuduğu defterle kafasındaki Raif Efendi'nin bambaşka kişiler olduğu anlaşılır.

Defterde, bir sergide gördüğü Maria Puder'in otoportresine hayran olan Raif Efendi'nin portrenin sahibiyle karşılaşınca başlayan tutkulu aşkın hüsranla sonuçlanmasıyla yaşadığı

yıkım travmanın temellerini atar ve fiziksel olarak da kendisini hissettirir. Karakter aşkın enkazında travmatik bir sonla yavaş yavaş hastalığa oradan da ölüme sürüklenir. Çünkü "âşıklar için sevgili, varoluşlarının yeniden yapılandırılması adına yeni bir dünya ve varoluş şeklidir" (Deveci, 2014: 170). Raif Efendinin travmatik bir sonla ölüme sürüklenen yaşamında Maria Puder aynı zamanda var olma/yeniden doğmanın bir diğer adıdır. Bu yüzden Raif Efendi, tüm benliğini tek bir nesneye (Maria Puder'e) endeksler: "*Artık Maria Puder, yaşamak için kendisine kayıtsız şartsız muhtaç olduğum bir insandı*" (Ali, 2022: 111). Raif Efendi'nin hayattaki varlığının sebebi olarak gördüğü kadına karşı duyduğu aşk aynı zamanda romanın sonunda yaşadığı trajik ölümün de simgesel olarak karşılığıdır.

Aşkın bu kadar baskın bir duygu olarak karakterde vuku bulmasında Arthur Schopenhauer'in "aşk genel olarak güçlü, ama yine de dizginlenebilir bir eğilim olarak görünen bir duygu, belli koşullarda bütün duygulardan daha şiddetli bir tutku haline girebilir ve böylece hiçbir kayıt tanımadan, önüne çıkan her engeli inanılmaz bir güç ve inatla ortadan kaldırır" (2019: 30) sözlerini destekleyici nitelikte ilerler. Raif Efendi için Maria Puder, kayıtsız şartsız yaşama sebebidir:

"Dünyada hiçbir şey, hiçbir kimse benim için o andaki Maria Puder kadar mühim ve kıymetli değildi. Ben bütün ömrümce bu anı beklemiş, bu insanı aramıştım." (Ali, 2022: 98).

Psikanalitik açıdan bu durum, kişinin kendini ön planda tutmasının ve narsistlik eğilimin ötesinde tüm yaşam enerjisinin tek bir noktada özellikle libidoda toplanmış olmasıdır. Raif Efendi'nin "*hayatım müddetince hep onu aramış, onu beklemiştim*" (s. 111) dediği Maria Puder'e karşı toplanan enerjinin oluşturduğu bağ aynı zamanda Jung'un anima arketipinin de karşılığıdır. Karakterin tüm yaşamında büyük bir boşluk ve istemsiz bir kopuş oluşturur.

Sabahattin Ali'nin roman dünyasındaki karakterlerin en belirgin özelliği, aşılması imkânsız bir ontolojik yalnızlık içine hapsolmuş olmalarıdır. Çünkü yaşanan, "modern hayat içinde

kaybolan, tutunamayan kadın ve erkek ideolojik çatışmaların yer aldığı kaba bir gerçeklik içinde doğal ayrıntılarda hissettirilen melankolik" (Uslu, 2017: 784) bir aşktır. Raif Efendi ve Maria Puder özelinde bu durum, Ramazan Korkmaz'ın (2015) ifadesiyle: Tarafların birbirlerine "çıkarsız", "samimi" ve "kayıtsız" bir biçimde bağlanarak mevcut yalnızlık sarmalından kurtulma iradesiyle somutlaşır. Ancak yazarın karakterlerine biçtiği bu hazin kader, trajik bir paradoksu birlikte oluşturur. İnsanın bir başka insana yaklaşabileceği o "muayyen had" aşıldığı anda, atılan her adım tarafları paradoksal bir şekilde birbirinden daha fazla uzaklaştırmaya başlar. Bu bağlamda roman kahramanları, kendi yalnızlıklarına hayatlarındaki kötü gidişatlara ve yazarın onlar için çizdiği kaderci anlayışa mahkûm edilmiş trajik piyonlardır.

Kaderci döngünün başlangıç noktası, Raif Efendi'nin Maria Puder'in kendisiyle tanışmadan önce onun sanatsal izdüşümü olan tablosuyla karşılaşmasıdır. Akademik bir perspektifle bakıldığında, Raif'in tabloya duyduğu tutku/aşk basit bir estetik beğeninin çok ötesinde; yazarın kahramanlarını içine çektiği yas, yalnızlık ve melankoli silsilesinin ilk kıvılcımıdır. Burada tablo, "kanlı canlı bir sevgilinin" yerini ikame eden cansız bir nesne olarak işlev görür. Tutkulu aşkın bu cansız nesneden canlı bir özneye (Maria Puder) geçişi ise ancak Maria'nın bu alakaya karşılık vermesiyle mümkün olur. Raif Efendi'nin, "*O zamana kadar bütün insanlardan esirgediğim alaka, hiç kimseye karşı tam manasıyla duymadığım sevgi sanki hep birikmiş ve muazzam bir kütle halinde şimdi bu kadına karşı meydana çıkmıştı*" (s. 111) sözleriyle ifade ettiği aşk itirafı, aslında yaklaşan büyük bir yıkımın ön habercisidir. Yazar, karakterinin yıllarca biriktirdiği bu devasa sevgi kütlesini açığa çıkararak, aslında onu bekleyen trajik sonu ve kaçınılmaz yalnızlığını hazırlamış olur. Bu yoğun duygusallık, romantik bir aşkın müjdecisi olmaktan ziyade, yazarın karakterlerine biçtiği kaderci trajedinin engellenemez bir sonucu olarak vuku bulur.

Ayrılık ve Belirsizliğin Yarattığı Kronik Stres ve Kırık Kalpler Sendromu

Raif'in Türkiye'ye dönüşü ve Maria'dan mektup alamadığı on yıl, travmanın "kuluçka" dönemidir. Kırık Kalpler Sendromu'nu tetikleyen unsur sadece ani şoklar değil, bazen de uzun süreye yayılan, atlatılamamış kederdir. Raif, Maria'nın onu unuttuğunu veya aldattığını düşündüğünde, kalbi kronik bir savunma mekanizmasına dönüşür:

"*İçimde bir şeylerin, sanki canlı bir kısmımın koptuğunu hissediyordum. Bu, sadece ruhsal bir acı değildi; sanki kalbim yerinden oynamış, bir daha yerine oturamayacak şekilde sarsılmıştı"* (Ali, 2022: 134).

Bu betimleme, tıp dilindeki sol karıncık disfonksiyonunun edebi bir karşılığıdır. Kalp, artık kanı değil, sadece kederi pompalamaktadır.

Sabahattin Ali'nin Kürk Mantolu Madonna anlatısı, sadece imkansız bir aşkın hikâyesi değil; aynı zamanda ayrılık travması ve "belirsizlik" olgusunun insan fizyolojisi üzerindeki tahrip edici etkisinin edebi bir dökümüdür. Eserde Raif Efendi karakterinin yaşadığı kronik stres süreci, modern tıbbın Takotsubo Kardiyomiyopatisi (Kırık Kalpler Sendromu) olarak tanımladığı tablonun tüm aşamalarını sergiler. Takotsubo kardiyomiyopatisi, stres hormonlarının (katekolaminler) kalbi sersemletmesiyle oluşur. Belirtileri arasında şiddetli göğüs ağrısı, nefes darlığı ve bayılma yer alır. Romanın Ankara kısımlarında, Raif Efendi'nin sürekli göğsünde bir baskı hissemesi, merdiven çıkarken zorlanması ve genel bir hayati yetmezlik içinde olması bu tabloyla tam örtüşür. Raif'in hastalığının "belirsiz" oluşu, dönemin doktorlarının kalpte bir tıkanıklık (enfarktüs) bulamaması ancak hastanın ölmesi, Kırık Kalpler Sendromu'nun tipik özelliğidir. Damarlar açıktır ancak kalp kası "sersemleşmiş"tir. Raif Efendi için Maria Puder'den ayrılış ve sonrasında gelen on yıllık haber alamama süreci, bir belirsizlik sarmalı yaratarak vücudun savunma mekanizmalarını yok eder. Ali, bu ontolojik boşluğu şu cümlelerle resmeder:

"*Hayatımda hiç bu kadar yalnız, bu kadar yardımsız ve zavallı kalmamıştım. Bütün dünya, bütün insanlar benim için yabancıydı; sadece o vardı... O da yoktu artık. Niçin gittiğini, nerede olduğunu, bir daha gelip gelmeyeceğini bilmiyordum"* (Ali, 2022: 124).

Bu "bilmeme" hali, beynin sürekli tehdit algısı üretmesine neden olarak Raif'i kronik stresin kucağına iter. Akademik literatürde şiddetli duygusal stresin, vücutta salgılanan aşırı katekolamin deşarjı yoluyla kalp kaslarını "sersemlettiği" (myocardial stunning) ve sol karıncığı felce uğrattığı bilinmektedir (Wittstein ve ark., 2005: 540). Raif Efendi'nin Maria'nın yokluğunda hissettiği fiziksel ağırlık, tıbbi bir semptom olarak karşımıza çıkar:

"Sanki içimde bir şey kopmuştu... Göğsümün üzerinde ağır bir taş varmış gibi nefes alamıyordum. Günlerce, haftalarca aynı donuk gözlerle duvara baktım. Etrafımdaki dünya silinmiş, geriye sadece göğsümdeki o bitmek bilmeyen sızı kalmıştı" (Ali, 2022: 142).

Burada betimlenen "göğüsteki sızı" ve "dispne" (nefes darlığı), stres kaynaklı kardiyomiyopatinin klinik bulgularıyla birebir örtüşmektedir (Lyon ve ark., 2016: 12). Karakter, on yıl boyunca maruz kaldığı bu belirsizlik ve kronik stres altında kalbinin fiziksel formunun bozulmasına (apikal balonlaşma) benzer bir ruhsal genişleme ve ardından gelen bir çöküş yaşar. Maria'nın ölüm haberini aldığı an, yıllarca süren stresin akut bir şoka dönüştüğü ve kalbin nihai olarak yenildiği noktadır:

"O günden sonra bir daha eski Raif olamadım. Kalbimde o kadar büyük bir boşluk açılmıştı ki, dünya içinden geçse dolmazdı... Her nefes alışım, sanki sonuncusuymuş gibi ağır ve zahmetliydi" (Ali, 2022: 158).

Sabahattin Ali'nin realizmi, karakterin duygusal dünyasındaki bu devinimi, somatik bir yıkımla taçlandırarak eseri "kalbin yenilgisi" üzerine kurulu bir patolojik başyapıta dönüştürür.

Maria'nın Ölümünün Öğrenilmesi: Terminal Safha

Romanın finalinde, Maria'nın aslında doğum yaparken öldüğünü ve ona sadık kaldığını öğrenmesi, Raif için "ikincil travma"dır. Bu bilgi, on yıldır taşıdığı öfkeyi vicdan azabına dönüştürür. İşte bu yoğun suçluluk duygusu, kalbin biyolojik olarak pes ettiği "terminal safha"yı başlatır:

"*Mektubu okuduktan sonra içimde hiçbir şey kalmadı. Ne bir isyan, ne bir feryat... Sadece büyük, sonsuz bir boşluk ve göğsümün ortasında hiç dinmeyen o keskin sızı*." (Ali, 2022: 154).

Sabahattin Ali'nin anlatısında Raif Efendi'nin Berlin'den ayrılışıyla başlayan kronik stres süreci, Maria Puder'in ölüm haberinin alınmasıyla birlikte geri dönüşü olmayan bir yıkıma, yani patolojik bir "terminal safha"ya evrilir. Bu aşama, akademik perspektifte sadece duygusal bir yas süreci değil; on yıl boyunca belirsizlikle beslenen kronik stresin, akut bir kardiyovasküler ve ruhsal iflasa dönüştüğü noktadır.

On yıl süren haber alamama halinin yarattığı belirsizlik sarmalı, Maria'nın ölüm haberiyle birlikte yerini kesin ve katı bir hiçliğe bırakır:

"*O günden sonra bir daha eski Raif olamadım. Kalbimde o kadar büyük bir boşluk açılmıştı ki, dünya içinden geçse dolmazdı. Vücudum artık ruhuma dar gelmeye başlamıştı. Her nefes alışım, sanki sonuncusuymuş gibi ağır ve zahmetliydi*" (Ali, 2022: 158).

Bu yazı, Takotsubo Kardiyomiyopatisi'nde gözlemlenen sol karıncığın uç kısmının genişleyerek pompalama işlevini yitirmesinin (terminal yetmezlik) edebi bir tasviridir. Terminal safhanın en belirgin özelliği, Raif Efendi'nin dış dünyaya karşı kurduğu tüm savunma mekanizmalarının ve ontolojik bağlarının kopmasıdır. Raif Efendi de acıyı ve aşkı uçlarda yaşar çünkü "insan ne kadar yüceyse, acısı da o ölçüde fazladır" (Schopenhauer, 2019: 70). Maria'nın aslında kendisine ihanet etmediğini, aksine bir çocuk bırakarak ve kendisine sadık kalarak

öldüğünü öğrenmesi, Raif için teselli değil, telafisi imkansız bir "geç kalmışlık" şoku yaratır. Bu durum, psikosomatik açıdan vücudun on yıl boyunca maruz kaldığı katekolamin baskısının, nihai bir şokla kalp kaslarında toksik bir yıkım yaratmasıyla açıklanır (Wittstein ve ark., 2005: 541).

Ali, bu terminal aşamadaki fiziksel ve ruhsal tükenişi karakterin ağzından şu şekilde derinleştirir:

"Sanki içimde bir şey kopmuştu... Göğsümün üzerinde ağır bir taş varmış gibi nefes alamıyordum... Geriye sadece göğsümdeki o bitmek bilmeyen sızı kalmıştı" (Ali, 2022: 142).

Karakterin yaşadığı bu "göğüsteki ağır taş" hissi, klinik olarak kalp yetmezliğine bağlı dispne begging anjina semptomlarının edebi izdüşümüdür (Lyon ve ark., 2016: 14). Akademik literatürde terminal safha, yaşamın fiziksel olarak devam ettiği ancak yaşamsal arzunun (libido) tamamen geri çekildiği bir süreci ifade eder. Raif Efendi'nin ölüm haberinden sonraki "yaşayan ölü" hali, benliğin sessizce biyolojik sonu beklemesidir: "*Vücudum artık ruhuma dar gelmeye başlamıştı*" (Ali, 2022: 158) ifadesi, ruhun bedensel kafesten kurtulma isteğini ve kalbin bu yükü taşımayacak kadar genişlediğini (apikal balonlaşma) simgeler. On yıl süren belirsizlikte kalp "bekleme modunda" kasılırken, ölüm gerçeğiyle birlikte bu kasılma yerini "salıvermeye" ve nihai iflasa bırakır. Yazar, "kahramanlarının çoğunu bir çıkmaza sürükler ve bu çıkmazların çoğu gizemli ölümlerle sonuçlanır. Ölmek, çoğu öykü kahramanın ontolojik anlamda varlığını anlamlandıramadığı huzursuz yaşamdan kaçma edimi olarak yer alır" (Uzun, 2021: 199). Bu durum adeta "saklanmış nevrotik anılar magmasının dışavurumu gibidir" (Korkmaz, 2015: 179). Sabahattin Ali, bu süreci klinik bir titizlikle işleyerek, ruhsal bir yaralanmanın nasıl terminal bir biyolojik vakaya dönüştüğünü; kalbin sadece mecazi değil, fizyolojik olarak da "kırılarak" sahibini ölüme sürüklediğini kanıtlamıştır.

Kürk Mantolu Madonna romanında Raif Efendi'nin organik/fiziksel rahatsızlıkları ile Kırık Kalpler Sendromu (Takotsubo Kardiyomiyopatisi) kriterleri arasındaki analitik ve edebi karşılaştırma tablosu aşağıdadır:

Kırık Kalpler Sendromu Kriterleri (Tıp)	**Raif Efendi'nin Romandaki Kritik Durumu (Edebiyat)**	**Metinden Hareketle Göstergeler / Alıntılar**
Tetikleyici Unsur: Sevilen birinin ani kaybı, şok hali, yoğun ayrılık acısı veya ağır duygusal travma.	Gecikmeli Gelen Hakikat Şoku: Maria'nın onu asla terk etmediğini, gerçekten öldüğünü ve geride ondan bir çocuk bıraktığını tren istasyonunda öğrenmesi.	Yıllarca süren sessizliğin ardından gelen bu ani haber, Raif Efendi'nin hayat enerjisini tamamen koparan bir kırılma noktası olur.
Fiziksel Belirtiler: Göğüs ağrısı, nefes darlığı, baş dönmesi, halsizlik ve kalp krizi benzeri akut çöküş.	Solunum Sıkıntısı ve Fiziksel Yıkım: Büyük şokun ardından hızla yatağa düşmesi, şiddetli öksürük krizleri, ateş ve nefes alamama vb. durumlar.	Genç meslektaşının, anlatıcının gözlemlerinde; Raif Efendi'nin evdeki odasında adeta nefessiz kalışı, bitkinliği, hiç kimseyle muhatap olmaması ve günden güne erimesi.

Fizyolojik Mekanizma: Stres hormonlarının kalbi geçici olarak felç etmesi, vücudun fizyolojik işlevini bozması.	Ruhun Bedeni Çürütmesi/Yok etmesi: Yıllarca içine attığı kederin ve son şokun organlarını bitirmesi, "içsel çürüme".	Romanda hastalığın basit bir üşütme değil, içeride biriken ve dışarı çıkamayan bir pürüz olduğu hissi uyandırılır.
Prognoz (Seyir): Yaşama iradesi ve destekle düzelebilir ancak yoğun stres altında ölümcül olabilecek kadar risklidir.	Yaşama İradesinin Kaybı (Kendi Kendini İmha): Doktorların müdahalesine ve ilaçlara karşı tamamen ilgisiz ve isteksiz olması, ölümü arzulaması.	Raif Efendi'nin ilaçları içmek istememesi ve anlatıcıya "Artık çok geç" der gibi bakması; vücudunun/ruhunun gitmek istediği yere (ölüme) teslim olması.

Tablo 1: Edebi bulgular ve Tıbbı Karşılıklar Analizi

Tablo 1'de de gösterilen ve romanda da sürekli tasvir edilen 'nefessizlik' ve 'tükenme' hissi, Takotsubo Sendromu'nun kalbin pompalama gücünü zayıflatması/sekteye uğratması neticesinde gelişen akut pulmoner ödem durumunun kusursuz bir edebi dönüşümüdür. Doktorların koyduğu zatürre teşhisi, dönemin kısıtlı tıp imkânları çerçevesinde yüzeysel bir tespitten ibarettir. Çünkü hastayı yatağa düşüren asıl patoloji fizyolojik değil, emosyonel kaynaklıdır. Raif Efendi'nin ilaç şişelerini komodinin üzerinde tozlanmaya bırakması ve tedaviyi sessizce reddetmesi, miyokardiyal sersemlemenin yarattığı yaşamsal apati ile birebir örtüşür:

Sürekli Halsizlik ve "İçten Çürüme": Romanda anlatıcı (genç meslektaşı), Raif Efendi'nin işe gelip giderken bile adeta yaşayan bir ölü gibi olduğunu, vücudunun ağır bir yük taşıyormuş gibi çöktüğünü gözlemler. Raif Efendi, yıllarca içine attığı kederi fiziken taşımakta zorlanır.

Ağır Yatak Hastalığı (Zatürre/Akciğer Rahatsızlığı Görünümü): Maria'nın ölüm haberini (ve onun aslında kendisinden bir çocuğu olduğunu) yıllar sonra o tren istasyonunda baldızından öğrendiği an, Raif Efendi için kırılma noktasıdır. Bu şokun ardından eve kapanır, yatağa düşer. Metinde sürekli öksürdüğü, nefes almakta zorlandığı ve ateşler içinde yandığı belirtilir.

Yaşama İradesinin Kaybı: Doktorlar onun hastalığına teşhis koysa ve ilaç verse de, anlatıcı Raif Efendi'nin ilaçları isteksizce içtiğini, hatta iyileşmek istemediğini fark eder. Vücudu, ruhunun gitmek istediği yere (ölüme) teslim olmaktadır.

SONUÇ

Sabahattin Ali, Raif Efendi karakteri aracılığıyla insan ruhunun kırılganlığını ve bu kırılganlığın bedensel yansımalarını dahi dâhiyane bir sezgiyle resmeder. Raif Efendi, tüberküloz veya grip gibi dışsal bir etkenden değil, tıp dünyasının "Kırık Kalpler Sendromu" olarak adlandırdığı, ruhsal acının kalbi fiziksel olarak parçalaması sonucunda ölür. Onun ölümü, Maria Puder'e duyulan ve on yıl boyunca sessizce büyütülen o devasa kederin somut bir neticesidir. Bu çalışma, edebiyatın tıp dünyasından yıllar önce "kalbin kırılmasının" gerçek bir ölüm sebebi olabileceğini keşfettiğini kanıtlamaktadır.

Sabahattin Ali'nin Kürk Mantolu Madonna adlı eseri, Raif Efendi'nin trajedisi üzerinden, ruhsal bir sarsıntının biyolojik bir terminal safhaya evrilişini eşsiz bir titizlikle kayda geçirmiştir. Çalışma boyunca incelenen "Ayrılık ve Belirsizliğin Yarattığı Kronik Stres" evresi, karakterin on yıl boyunca maruz kaldığı yoğun katekolamin baskısının, vücudun savunma mekanizmalarını nasıl aşındırdığını ortaya koymuştur. Raif efendinin hastalığı başlangıçta organik/fiziksel bir rahatsızlık olarak da görünse de bu durum aslında ruhsal olarak hayata veda eden bir bedenin çöküşüdür. Raif Efendi'nin ölümü, bir organ yetmezliği değil; Maria Puder patolojisinin kalpte yarattığı akut morfolojik deformasyondur. Yazar, psikosomatik tıbbın ve Takotsubo Sendromu'nun sınırlarını, edebiyatın estetik imkanlarıyla onlarca yıl öncesinden

çizerek romana tıbbi bir boyut da kazandırır. Raif Efendi, kalbi göğsüne sığmadığı için değil, kalbi Berlin'deki bir sergide asılı kalan o portrenin içine sıkışıp büzüldüğü için fiziken tükenerek hayatının sonuna gelir.

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IDDSI AND DYSPHAGIA MANAGEMENT

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Abstract

Dysphagia is a clinical condition characterized by difficulty in passing food from the mouth to the stomach due to disorders in swallowing function. It is especially common in elderly individuals, post-stroke patients and people with neurological disorders, and can lead to serious complications such as aspiration pneumonia, malnutrition and dehydration. Therefore, dysphagia is not only an individual health problem, but also a significant burden on public health. Long-term hospitalizations, increased readmission rates, and rising treatment costs put additional pressure on healthcare systems.

Clinical evaluation methods (FEES, VFSS) and multidisciplinary team approach play a critical role in dysphagia management. Coordinated care by nurses, dietitians and speech therapists is vital to ensuring safe nutrition and preventing complications. Positioning techniques, swallowing exercises, consistency adjustments and diet modifications are used during the treatment process. At this point, the International Dysphagia Diet Standardization Initiative (IDDSI) was developed in 2015 and offers a universal system that classifies foods and liquids between 0 and 7 according to their consistency. The suitability of food and liquids is evaluated with IDDSI test protocols (flow test, fork drop test, spoon bending test). In addition, identifying food textures that pose a risk of choking and using transition foods are among the important strategies that support safe swallowing.

In conclusion, the IDDSI framework increases patient safety in dysphagia management, reduces complications, and ensures standardization in clinical practices. This study comprehensively summarizes current approaches and the role of IDDSI in clinical practice.

Keywords: Dysphagia, IDDSI, Swallowing Disorder, Clinical Management, Nutrition

IDDSI VE DİSFAJİ YÖNETİMİ

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Özet

Disfaji, yutma fonksiyonunda ortaya çıkan bozukluklar nedeniyle ağızdan mideye gıda geçişinde güçlük yaşanmasıyla karakterize edilen klinik bir durumdur. Özellikle yaşlı bireylerde, inme sonrası hastalarda ve nörolojik bozukluklara sahip kişilerde sık görülmekte olup aspirasyon pnömonisi, malnütrisyon ve dehidratasyon gibi ciddi komplikasyonlara yol açabilmektedir. Bu nedenle disfaji yalnızca bireysel bir sağlık sorunu değil, aynı zamanda toplum sağlığı açısından da önemli bir yük oluşturmaktadır. Uzun süreli hastane yatışları, yeniden yatış oranlarının artması ve tedavi maliyetlerinin yükselmesi, sağlık sistemleri üzerinde ek baskı yaratmaktadır.

Disfaji yönetiminde klinik değerlendirme yöntemleri (FEES, VFSS) ve multidisipliner ekip yaklaşımı kritik rol oynamaktadır. Hemşireler, diyetisyenler ve konuşma terapistleri tarafından yürütülen koordineli bakım, güvenli beslenmeyi sağlamak ve komplikasyonları önlemek açısından hayati öneme sahiptir. Tedavi sürecinde pozisyonlama teknikleri, yutma egzersizleri, kıvam ayarlamaları ve diyet modifikasyonları kullanılmaktadır. Bu noktada Uluslararası Disfaji Diyeti Standardizasyon Girişimi (IDDSI), 2015 yılında geliştirilmiş olup gıdaların ve sıvıların kıvamına göre 0–7 arasında sınıflandırma yapan evrensel bir sistem sunmaktadır. IDDSI test protokolleri (akış testi, çatal damlatma testi, kaşık eğme testi) ile gıda ve sıvıların uygunluğu değerlendirilmektedir. Ayrıca boğulma riski taşıyan gıda tekstürlerinin belirlenmesi ve geçiş gıdalarının kullanımı, güvenli yutmayı destekleyen önemli stratejiler arasında yer almaktadır.

Sonuç olarak, IDDSI çerçevesi disfaji yönetiminde hasta güvenliğini artırmakta, komplikasyonları azaltmakta ve klinik uygulamalarda standartlaşmayı sağlamaktadır. Bu çalışma, güncel yaklaşımları ve IDDSI'nin klinik uygulamalardaki rolünü kapsamlı biçimde özetlemektedir.

Anahtar Kelimeler: Disfaji, IDDSI, Yutma Bozukluğu, Klinik Yönetim, Beslenme.

1. GİRİŞ

Disfaji; nöromotor bozukluklar, yapısal anomaliler veya fonksiyonel yetersizlikler sonucunda yutmanın herhangi bir evresinde ortaya çıkan ve gıda ile sıvı alımını önemli ölçüde kısıtlayan klinik bir tablodur. Epidemiyolojik veriler incelendiğinde, disfajinin toplumda yaklaşık %2–3 oranında görüldüğü ve 65 yaş üzeri bireylerde bu oranın %15–22'ye yükseldiği bildirilmektedir (Matsuo & Palmer, 2022). Akut inme geçiren hastalarda disfaji prevalansının %40–78 arasında değiştiği bilinmekte; nörodejeneratif hastalıklar, baş-boyun kanserleri ve yoğun bakım süreçlerinde de benzer yüksek oranlar gözlemlenmektedir (Clavé & Shaker, 2021). Bu yaygınlık, disfajiyi küresel ölçekte önemli bir halk sağlığı sorunu hâline getirmektedir.

Yutma; oral, faringeal ve özofageal olmak üzere üç temel evreden oluşan nöromüsküler bir süreçtir. Bu sürecin herhangi bir evresindeki aksama yalnızca aspirasyon pnömonisi, malnütrisyon ve dehidratasyon gibi akut komplikasyonlara değil; aynı zamanda yaşam kalitesinin belirgin biçimde düşmesine, sosyal izolasyona ve artan mortalite riskine de zemin hazırlamaktadır (Baijens et al., 2023). Sağlık sistemleri açısından değerlendirildiğinde, disfajiye bağlı komplikasyonların hastane yatış sürelerini uzattığı, yeniden yatış oranlarını artırdığı ve tedavi maliyetlerini önemli ölçüde yükselttiği görülmektedir (Madhavan et al., 2021). ABD'de disfajiye bağlı yıllık sağlık harcamalarının 50 milyar doları aştığı tahmin edilmekte olup Avrupa ülkelerinde de benzer ekonomik yükler rapor edilmektedir.

Disfaji yönetiminde son yıllarda elde edilen en önemli kazanımlardan biri, 2015 yılında yayımlanan ve 2019'da güncellenen Uluslararası Disfaji Diyeti Standardizasyon Girişimi'dir (IDDSI). IDDSI, gıda ve sıvıları 0'dan 7'ye uzanan sekiz düzeyde sınıflandıran kapsamlı bir çerçeve sunmakta; böylece farklı ülkelerde, farklı klinik ortamlarda ve farklı disiplinler arasında ortak bir dil oluşturmayı hedeflemektedir (IDDSI, 2019). Bu standardizasyon çabası, ülkeden ülkeye değişen tutarsız terminoloji ve uygulamalar nedeniyle yaşanan güvenlik risklerini azaltmak amacıyla 33 ülkeden 500'ü aşkın paydaşın katılımıyla hayata geçirilmiştir. Bu çalışmanın amacı, disfaji yönetiminde kullanılan güncel değerlendirme yöntemlerini, tedavi stratejilerini ve IDDSI çerçevesinin klinik uygulamalardaki yerini kapsamlı biçimde ele almaktır.

2. GELİŞME

2.1. Disfajinin Tanımı, Sınıflandırması ve Epidemiyolojisi

Disfaji, etiyolojisi ve mekanizması bakımından iki temel kategori altında incelenmektedir: orofaringeal disfaji ve özofageal disfaji. Orofaringeal disfaji, yutmanın oral ve faringeal evrelerini etkileyen; nörolojik hastalıklar, kas hastalıkları ve yapısal bozukluklardan kaynaklanan bir tablodur. Özofageal disfaji ise yiyeceklerin özofagustan geçişinde yaşanan güçlükleri ifade eder ve daha çok gastroenteroloji kapsamında değerlendirilir (Wirth et al., 2021). Orofaringeal disfaji; inme, Parkinson hastalığı, multipl skleroz ve demans gibi nörolojik tablolarla güçlü bir ilişki sergilemekte olup yaşlılıkla birlikte görülen fizyolojik yutma kası kaybı ve duyusal gerilemeler presbifaji olarak adlandırılmaktadır.

Küresel epidemiyolojik verilere göre disfaji, yüksek gelirli ülkelerde hastaneye yatışların önemli bir sebebi olmaya devam etmektedir. Amerikan Konuşma-Dil-İşitme Derneği'nin (ASHA) raporlarına göre ABD'de yılda 15 milyonun üzerinde bireyin disfajiden etkilendiği tahmin edilmektedir. Parkinson hastalığında bu oran %70–90'a ulaşmakta; demansa eşlik eden yutma güçlükleri ise hastalığın ileri evrelerinde neredeyse evrensel bir bulgu niteliği taşımaktadır (Speyer et al., 2022). Türkiye'de ise sistemik epidemiyolojik çalışmalar oldukça sınırlı kalmakla birlikte, geriatrik servislerde ve nöroloji birimlerinde disfajinin önemli bir morbidite nedeni olduğu bildirilmektedir (Yılmaz & Küçükdeveci, 2022). COVID-19 sonrası dönemde uzun süreli mekanik ventilasyon bağlantılı yutma bozukluklarının gündeme gelmesi, bu alanda yeni araştırma ihtiyaçlarını da beraberinde getirmiştir (Frajkova et al., 2022).

Disfajinin psikososyal boyutu da en az klinik komplikasyonları kadar önem taşımaktadır. Yemek yeme ve sosyal bir arada olma etkinliklerindeki kısıtlamalar; hastalarda anksiyete, depresyon ve sosyal izolasyona yol açabilmekte; bu durum aynı zamanda bakım verenler üzerinde de ciddi bir yük oluşturmaktadır. Bu çok katmanlı tablo, disfajinin yalnızca tıbbi değil, bütüncül bir bakış açısıyla ele alınması gerektiğini ortaya koymaktadır (Verdonschot et al., 2023).

2.2. Klinik Değerlendirme Yöntemleri

Disfajinin doğru şekilde değerlendirilebilmesi için hem klinik tarama araçları hem de enstrümantal yöntemler birlikte kullanılmaktadır. Klinik taramada Yeme Değerlendirme Aracı (EAT-10) ve Hacim-Viskozite Yutma Testi (V-VST) en sık başvurulan araçlar arasında yer almaktadır. EAT-10; geçerliliği ve güvenilirliği kanıtlanmış, uygulaması pratik bir öz-bildirim ölçeği olup 10 sorudan oluşmaktadır (Belafsky et al., 2020). V-VST ise farklı hacim ve kıvam kombinasyonlarını test ederek aspirasyon ile penetrasyon riskini ortaya koyması bakımından yatakbaşı taramada öne çıkmaktadır. Yutma Kalite Yaşamı Ölçeği (SWAL-QOL) ise hastaların yaşam kalitesi ve psikososyal etkilerini değerlendirmek amacıyla kullanılan kapsamlı bir ölçektir.

Enstrümantal değerlendirmede ise Videofloroskopik Yutma Çalışması (VFSS) ve Fleksibl Endoskopik Yutma Değerlendirmesi (FEES) altın standart kabul edilmektedir. VFSS, yutmanın oral, faringeal ve özofageal evrelerini dinamik olarak görüntülerken; FEES, endoskopik yöntemle faringeal aşamayı ayrıntılı biçimde incelemekte ve ışıma içermemesi, yatakbaşı uygulanabilirliği gibi avantajlar sunmaktadır. Bu iki yöntem, aspirasyonun zamanlamasını ve yutma bozukluğunun kapsamını belirlemede birbirini tamamlar (Langmore, 2021). Son yıllarda ise yüksek çözünürlüklü manometri (HRM) ve ultrasonografi gibi ileri teknolojiler de klinik değerlendirmelerde kullanılmaya başlanmış; yapay zeka destekli görüntü analizinin tanısal sürece entegrasyonuna yönelik ilk araştırmalar da literatürde yer bulmaya başlamıştır (Rommel & Hamdy, 2021).

2.3. IDDSI Çerçevesi: Geliştirme Süreci ve Düzeyler

Uluslararası Disfaji Diyet Standardizasyon Girişimi (IDDSI), farklı ülkelerde kullanılan disfaji diyet sınıflamalarındaki terminolojik farklılıkları ortadan kaldırmak amacıyla oluşturulmuş ve 2015 yılında resmi olarak duyurulmuştur. Bu çerçeve, 0'dan 7'ye kadar uzanan sekiz basamaklı bir sistemden oluşmaktadır. Sıvılar için 0 (İnce Sıvı) ile 4 (Çok Koyu/Blendırlanmış) arasındaki düzeyler tanımlanırken; katı gıdalar için 3 (Yumuşatılmış) ile 7 (Normal) arası kategoriler kullanılmaktadır (IDDSI, 2019). 3. ve 4. düzeyler hem sıvı hem de gıda kategorisinde yer alarak iki boyutu birleştiren geçiş alanlarını temsil etmektedir. Böylece hem klinisyenler hem de araştırmacılar için ortak bir dil oluşturulması hedeflenmiştir.

IDDSI'nin güvenilirliğini ve uygulanabilirliğini artırmak amacıyla çeşitli test protokolleri geliştirilmiştir. Akış testi; 10 ml sıvının 10 saniye içinde 10 ml'lik şırıngadan ne kadar aktığını ölçerek sıvıların viskozitesini sınıflandırır. Çatal damlatma testi, gıdanın çataldan damlayıp damlamadığına veya çatala yapışıp yapışmadığına bakarak kıvamı değerlendirir. Kaşık eğme testi ise gıdanın kaşıktan serbestçe akıp akmadığını gözlemleyerek uygun IDDSI düzeyini belirlemeye yardımcı olur (Cichero et al., 2021). Bu testlerin klinik ortamlarda pratik biçimde uygulanabilmesi, farklı merkezler arasında tutarlılığı artırmakta ve hasta güvenliğini güçlendirmektedir. 2019 yılındaki revizyon sürecinde terminoloji netleştirilmiş, düzey tanımlamaları genişletilmiş ve test protokolleri güncellenerek uluslararası erişilebilirlik pekiştirilmiştir.

Sonuç olarak, IDDSI hem standardizasyonu sağlayan evrensel bir sınıflama sistemi hem de klinik ortamlarda uygulanabilirliği kolaylaştıran test protokolleri ile disfaji yönetiminde önemli bir referans noktası haline gelmiştir. Nişasta ve ksantan gam bazlı kıvam artırıcıların IDDSI düzeyleriyle uyumlu biçimde kullanılması, gıda endüstrisi ile klinisyenler arasındaki iş birliğini de zorunlu kılmaktadır (Steele et al., 2022).

2.4. IDDSI'nin Klinik ve Toplumsal Uygulamaları

IDDSI çerçevesi, klinisyenlerin yanı sıra gıda teknologlarına ve bakım hizmeti sağlayıcılarına da rehberlik etmektedir. Diyet tekstürüne uyum, aspirasyon riskinin azaltılmasında belirleyici bir etken olup IDDSI uyumlu diyet düzenlemelerinin aspirasyon pnömonisi sıklığını önemli ölçüde düşürdüğü gösterilmiştir (Steele et al., 2022). Hastaların besin alımını artırmak, yeterli hidrasyon sağlamak ve malnütrisyonu önlemek için diyetisyen desteğiyle kişiselleştirilmiş beslenme planlarının hazırlanması kritik önem taşımaktadır (Beck & Sura, 2023). Kıvamlaştırılmış sıvılara uyumun artırılması ise klinisyenlerin sıklıkla karşılaştığı pratik güçlükler arasındadır; hastaların koyulaştırılmış sıvıların tat ve dokusunu beğenmemesi, yeterli sıvı alımını tehlikeye atabilmektedir.

IDDSI'nin Türkiye'deki uygulamalarına bakıldığında çerçevenin henüz tam anlamıyla standardize edilmediği, ancak konuşma dili ve yutma terapisi alanındaki akademik çalışmaların bu boşluğu gidermeye yönelik adımlar attığı görülmektedir (Öztürk & Arslan, 2023). Hastane mutfakları ve uzun süreli bakım tesisleri açısından IDDSI uyumlu gıda hazırlama süreçleri hâlâ gelişim aşamasındadır. Bakım ortamları arasındaki geçiş dönemlerinde standardize edilmiş IDDSI protokollerinin kullanılması, özellikle taburculuk süreçlerinde güvenlik açıklarını en aza indirmek açısından büyük önem taşımaktadır. Bu bağlamda hemşirelerin ve konuşma terapistlerinin iş birliğiyle yürütülen multidisipliner yaklaşımların, disfaji yönetiminde hasta güvenliğini ve yaşam kalitesini artırdığı çeşitli çalışmalarda vurgulanmıştır (Dziewas et al., 2021).

2.5. Tedavi Yaklaşımları ve Rehabilitasyon

Disfaji rehabilitasyonunda kompansatuar ve rehabilitatif stratejiler olmak üzere iki temel yaklaşım benimsenmektedir. Kompansatuar stratejiler arasında baş eğme (chin-down), baş döndürme ve Mendelsohn manevrası gibi pozisyonlama teknikleri yer almakta; bu teknikler yutma sırasında aspirasyon riskini azaltmayı hedeflemektedir. Bunların yanı sıra küçük lokma ve yavaş beslenme alışkanlıkları, çift yutma gibi davranışsal düzenlemeler de kompansatuar yaklaşımın ayrılmaz bir parçasını oluşturmaktadır. Rehabilitatif yaklaşımlarda ise Shaker egzersizi, effortful swallow ve nöromüsküler elektriksel stimülasyon (NMES) gibi kas güçlendirme protokolleri uygulanmaktadır (Rofes et al., 2022). Lingual kuvvet antrenmanı ve Iowa Oral Performance Instrument (IOPI) kullanımı da nörolojik kökenli disfajide etkinliği gösterilmiş yöntemler arasında yer almaktadır (Krekeler et al., 2021).

Farmakolojik tedavi seçenekleri açısından kapsaisin ve piperidinin duyusal uyarı mekanizmaları aracılığıyla yutma refleksini güçlendirdiğine dair kanıtlar giderek artmaktadır (Ortega et al., 2023). Nörostimülasyon alanında ise transkraniyal manyetik stimülasyon (TMS) ve transkraniyal doğru akım stimülasyonu (tDCS) gibi non-invazif yöntemlerin nöroplastisiteyi desteklediği ve tedavi etkinliğini artırdığı bildirilmektedir (Momosaki et al., 2022). Dijital sağlık platformları ve teletıp uygulamaları da disfaji takibinde giderek yaygınlaşan araçlar arasına girmiş; bu yöntemler özellikle pandemi döneminde

ve hareketliliği kısıtlı hastalar için uzaktan değerlendirme ve tedavi sürekliğinin sağlanmasında kritik bir işlev üstlenmiştir (Borders et al., 2022).

3. SONUÇ

Disfaji, giderek artan prevalansı, çok boyutlu klinik etkileri ve neden olduğu ciddi komplikasyonlarla küresel ölçekte önem kazanan bir halk sağlığı sorunudur. Bu çalışmada ele alınan güncel kanıtlar, erken ve kapsamlı değerlendirmenin disfajiye bağlı komplikasyonları önlemedeki belirleyici rolünü açıkça ortaya koymaktadır. Konuşma dili ve yutma terapistleri, diyetisyenler, hemşireler ve hekimlerin koordineli biçimde hareket ettiği multidisipliner ekip modelinin hasta sonuçlarını olumlu yönde etkilediği pek çok çalışmada kanıtlanmıştır (Dziewas et al., 2021). Aspirasyon pnömonisi ve malnütrisyon gibi önlenebilir komplikasyonların azaltılmasında bu bütüncül yaklaşımın vazgeçilmez olduğu görülmektedir.

IDDSI çerçevesi, uluslararası terminoloji birliği açısından devrim niteliğinde bir katkı sunmaktadır. Gıda ve sıvı kıvamının standart test protokolleriyle nesnel biçimde değerlendirilebilmesi, klinisyenler, bakım personeli ve gıda endüstrisi aktörleri arasında ortak bir dil kurulmasını sağlamaktadır. Bu standardizasyonun faydası yalnızca klinik güvenlikle sınırlı kalmayıp, farklı kurumlar ve coğrafyalar arasında bakım sürekliliğini güvence altına alma bakımından da belirleyici bir işlev üstlenmektedir. Türkiye özelinde ise IDDSI'nin sağlık kurumlarında sistematik biçimde benimsenmesi, ulusal standartların oluşturulması ve sağlık profesyonellerinin bu konuda kapsamlı eğitim alması, önümüzdeki dönemin öncelikli hedefleri arasında yer almalıdır.

Sonuç olarak, disfaji yönetimi; bütüncül hasta bakımı, kanıta dayalı protokollerin uygulanması ve sürekli mesleki gelişimin bir araya geldiği dinamik bir alandır. IDDSI gibi uluslararası çerçevelerin yerel klinik pratikle bütünleştirilmesi, disfajili bireylerin güvenliğini, beslenme durumunu ve yaşam kalitesini artırmak için vazgeçilmez bir öneme sahiptir. Bundan sonraki araştırmaların; uzun dönemli klinik etkinlik verilerinin elde edilmesine, farklı hasta gruplarında IDDSI uyumunun değerlendirilmesine, Türk popülasyonuna özgü epidemiyolojik verilerin derlenmesine ve teknoloji destekli izleme sistemlerinin geliştirilmesine odaklanması önerilmektedir.

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ANALYSIS OF SIGNAL STRENGTH FROM A LOCAL ADS-B RECEIVER STATION USING ARTIFICIAL NEURAL NETWORKS

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Abstract

The Automatic Dependent Surveillance-Broadcast (ADS-B) system has become the cornerstone of modern air traffic surveillance, fundamentally transforming how aircraft positions and flight data are monitored globally. By integrating satellite-based navigation systems with onboard transponders, ADS-B periodically broadcasts the aircraft's coordinates, altitude, velocity, and identification data, typically over the 1090 MHz Mode S Extended Squitter (ES) data link. Unlike traditional primary and secondary surveillance radars that rely on active interrogation and mechanical scanning cycles, ADS-B offers a significantly higher data update rate. Due to these features, it plays a vital role in the safe determination of horizontal and vertical separation limits, optimization of fuel consumption, and enhancement of overall flight safety. The establishment of low-cost, customized ground stations allows independent researchers to directly access unfiltered raw data. This approach is highly effective for regional airspace monitoring, signal quality assessment, and the development of local prediction models. However, the Received Signal Strength Indicator (RSSI) of the data received by such independent stations exhibits variability. It displays complex and nonlinear structures influenced by environmental factors, station geometry, and flight dynamics. Artificial Neural Networks (ANNs) have proven to be extremely powerful tools for solving such nonlinear problems in complex datasets. Utilizing ANN algorithms on real-world, locally collected ADS-B data presents a significant opportunity to derive airspace-specific insights and build robust prediction models. This study presents a comprehensive analysis using flight data collected from a uniquely established ADS-B ground station. The primary objective of the study is to examine this local dataset using the ANN method and perform RSSI estimation based on flight parameters. Initially, the RSSI estimation algorithm and implementation steps are detailed. In this context, the processes of creating and uploading the multidimensional dataset are explained. The pre-processing and normalization steps used to make the data suitable for the analysis model are specified. The MLPRegressor architecture and selected hyperparameter definitions are presented. The estimation process through forward propagation and the weight update mechanism (backpropagation) that minimizes the error margin are discussed. In the final stage, performance metrics measuring the success of the model and validation results are analysed.

Keywords: ADS-B Surveillance, Artificial Neural Networks, RSSI Estimation

YEREL BİR ADS-B ALICI İSTASYONU VERİLERİNİN YAPAY SİNİR AĞLARI İLE ANALİZİ

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Özet

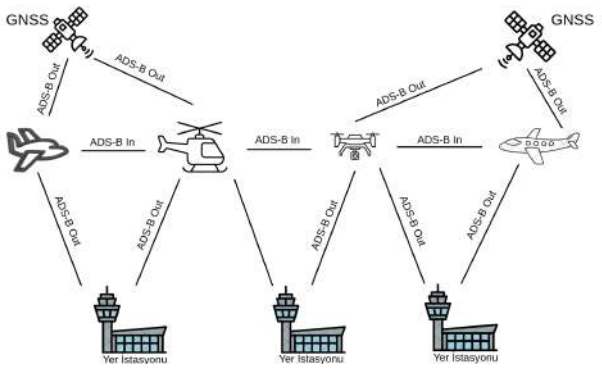
Otomatik Bağımlı Gözetim-Yayın (ADS-B) sistemi, uçakların konum ve uçuş verilerinin dünya genelinde izlenme biçimini kökten değiştirerek modern hava trafik gözetiminin temel taşı haline gelmiştir. ADS-B, uydu tabanlı seyrüsefer sistemlerini uçaktaki transponder'lar ile entegre ederek; uçağın koordinatlarını, irtifasını, hızını ve kimlik bilgilerini, genellikle 1090 MHz Mode S ES Genişletilmiş Yayın (Extended Squitter) veri ağı üzerinden periyodik olarak yayınlar. Aktif sorgulama ve mekanik tarama döngülerine dayanan geleneksel birincil ve ikincil gözetim radarlarının aksine ADS-B, çok daha yüksek bir veri güncelleme periyodu sunar. Bu özellikleri sayesinde, güvenli bir şekilde yatayda ve dikeyde uçaklar arası mesafe limitlerinin belirlenmesi, yakıt tüketiminin optimize edilmesinde ve genel uçuş emniyetinin artırılmasında hayati bir rol oynamaktadır. Düşük maliyetli ve özgün yer istasyonlarının kurulması, bağımsız araştırmacıların filtrelenmemiş ham verilere doğrudan erişmesine olanak tanımaktadır. Bu yaklaşım bölgesel hava sahası izleme, sinyal kalitesi değerlendirmesi ve yerel tahmin modellerinin geliştirilmesi için oldukça etkilidir. Ancak, bu tür bağımsız istasyonlar tarafından alınan verilere ait Alınan Sinyal Gücü Göstergesi (Received Signal Strength Indicator-RSSI) değişkenlik göstermektedir. Çevresel faktörler, istasyon geometrisi, uçuş dinamiklerinden etkilenen karmaşık ve doğrusal olmayan yapılar sergiler. Yapay Sinir Ağları, karmaşık veri setlerindeki bu tür doğrusal olmayan problemleri çözmek için son derece güçlü araçlar olduklarını kanıtlamışlardır. Gerçek dünyadan, yerel olarak toplanmış ADS-B verileri üzerinde ANN algoritmalarından yararlanmak, hava sahasına özgü çıkarımlar yapmak ve dayanıklı tahmin modelleri oluşturmak adına önemli bir fırsat sunmaktadır. Bu çalışmada, özgün olarak kurulmuş bir ADS-B yer istasyonundan toplanan uçuş verileri sayesinde kapsamlı bir analiz sunulmaktadır. Çalışmanın temel amacı, ANN yöntemini kullanarak bu yerel veri setini incelemek ve uçuş parametrelerine bağlı olarak RSSI tahmini gerçekleştirmektir. Öncelikle RSSI tahmin algoritması ve uygulama adımları detaylandırılmıştır. Bu kapsamda, çok boyutlu veri setinin oluşturulması ve sisteme yüklenmesi süreçleri açıklanmıştır. Verilerin analiz modeline uygun hale getirilmesi için kullanılan ön işleme ve normalizasyon adımları belirtilmiştir. MLPRegressor mimarisi ve seçilen hiperparametre tanımlamaları sunulmuştur. İleri besleme (forward propagation) ile tahminleme süreci ve hata payını minimize eden ağırlık güncelleme mekanizması (backpropagation) ele alınmıştır. Son aşamada ise, modelin başarısını ölçen performans metrikleri ve doğrulama sonuçları analiz edilmiştir.

Anahtar Kelimeler: ADS-B Gözetimi, Yapay Sinir Ağları, RSSI Tahmini

1. Giriş

Uluslararası Sivil Havacılık Örgütü (ICAO), Avrupa ve Amerika Birleşik Devletleri ile birlikte son yirmi yılda Otomatik Bağımlı Gözetim-Yayın (ADS-B) teknolojisi üzerine kapsamlı araştırma ve geliştirme faaliyetleri yürütmüştür. Bu teknolojiye ilişkin standartlar kamuoyuna açıktır. Bu gelişmelerin bir sonucu olarak, ADS-B tabanlı gözetim sistemleri günümüzde dünya çapında iş birlikçi Hava Trafik Kontrolü (ATC) için yeni nesil gözetim teknolojisi olarak kullanılmaktadır. ADS-B; uydu tabanlı konumlandırma teknolojisini, hava aracı aviyonik sistemlerini ve yer tabanlı gözetim altyapısını entegre eden gelişmiş bir hava gözetim teknolojisidir. Bu sistem aracılığıyla, ADS-B donanımına sahip hava araçları; kimlik, konum, irtifa ve hız gibi uçuş bilgilerini belirli aralıklarla otomatik olarak yayınlayabilmektedir. Geleneksel yer tabanlı radar sistemlerinden ayrılan ADS-B, Küresel Konumlama Sistemi (Global Positioning System- GPS) sinyallerinden yararlanarak önemli ölçüde daha hızlı ve daha yüksek doğrulukta konum bilgisi sağlamaktadır. Bu bilgiler, diğer hava araçları ve hava trafik kontrol üniteleri tarafından eş zamanlı olarak alınabilmekte; böylece pilotların ve kontrolörlerin aynı hava trafiği resmini gerçek zamanlı olarak görmelerine olanak tanımaktadır. Bu durum, hava trafiği emniyetinin artırılmasına ve hava sahasının daha verimli yönetilmesine önemli ölçüde katkı sağlamaktadır.

ADS-B sistemi temel olarak "ADS-B Out" ve "ADS-B In" olmak üzere iki ana işlev üzerinden değerlendirilmektedir. "ADS-B Out", hava aracının GPS tabanlı konumunu ve diğer uçuş bilgilerini hava trafik kontrol ünitelerine ve yakındaki diğer hava araçlarına yayınlamasını ifade eder. Diğer yandan "ADS-B In", uygun donanıma sahip hava araçlarının diğer hava araçları tarafından yayınlanan ADS-B mesajlarını almasına olanak tanıyarak; durumsal farkındalık, mesafe koruma (In-Spacing) ve havada öz-ayrım (Airborne Self-Separation) gibi gelişmiş uygulamalara imkân sağlar. Günümüzde birçok ülke ADS-B Out işlevini zorunlu kılmış olsa da ADS-B In uygulamaları çoğunlukla geleceğe yönelik operasyonel iyileştirmeler kapsamında değerlendirilmektedir. Bu bağlamda, "ADS-B Out"un günümüzü, "ADS-B In"in ise geleceği temsil ettiği ifade edilebilir (Li, 2020).



Şekil 1. ADS-B In & Out Gösterimi

Şekil 1'de modern hava trafik gözetiminin temelini oluşturan ADS-B sisteminin operasyonel mimarisini ve veri akışı özetlemektedir. Şekil 1'de gösterildiği üzere, hava platformları (uçaklar, helikopterler ve İHA'lar), GNSS uydularından aldıkları hassas konum bilgilerini "ADS-B Out" aracılığıyla yer istasyonlarına ve yakındaki diğer hava araçlarına sürekli olarak yayınlar. Eş zamanlı olarak, "ADS-B In" kabiliyeti sayesinde hava araçları birbirlerinin konum, hız ve irtifa verilerini doğrudan alarak pilotlara veya otonom sistemlere yüksek derecede durumsal farkındalık sağlar. Bu iki yönlü veri ekosistemi, yer istasyonlarının radar kapsama alanı dışındaki bölgelerde bile güvenli ve etkili bir hava trafik yönetimini mümkün kılar. ADS-B tabanlı hava trafiği gözetim sistemlerinin yaygınlaşmasıyla birlikte, bu sistemlerden elde edilen verilerin doğruluğu ve güvenilirliği kritik bir araştırma alanı haline gelmiştir. ADS-B mesajlarının alımında önemli bir metrik olan Alınan Sinyal Gücü Göstergesi (RSSI); sadece hava aracı ile yer alıcısı arasındaki mesafeye bağlı olmayıp, aynı zamanda irtifa, mesafe, hız, baş açısı, sıcaklık, atmosferik basınç, gövde gölgelemesi (airframe shadowing) ve elektromanyetik yayılım koşulları gibi çok sayıda parametreden de etkilenmektedir. Bu durum, ADS-B sinyallerinin fiziksel yayılım özelliklerinin ve performans limitlerinin daha ayrıntılı bir şekilde analiz edilmesini zorunlu kılmaktadır. Bu çalışma, özgün olarak kurulmuş bir ADS-B yer istasyonundan elde edilen gerçek uçuş verilerini kullanarak, uçuş parametreleri ve meteorolojik koşullara bağlı olarak RSSI değerini Yapay Sinir Ağları yöntemiyle tahmin etmeyi amaçlamaktadır. Çalışma kapsamında; yerel istasyon tarafından toplanan veri seti üzerinden mesafe, irtifa, hız, dikey hız ve baş açısı gibi temel uçuş parametrelerinin yanı sıra sıcaklık, nem, rüzgâr ve yağış gibi meteorolojik değişkenler girdi olarak kullanılmıştır. Bu veri setleri kullanılarak ANN yöntemi ile RSSI sinyal gücü değerlerinin tahmini gerçekleştirilmiştir. Geliştirilen bu modelleme yaklaşımıyla, değişken uçuş dinamikleri ve atmosferik koşullar altında sinyal yayılım performansının önceden kestirilmesi ve sistem güvenilirliğinin analiz edilmesi sağlanmıştır.

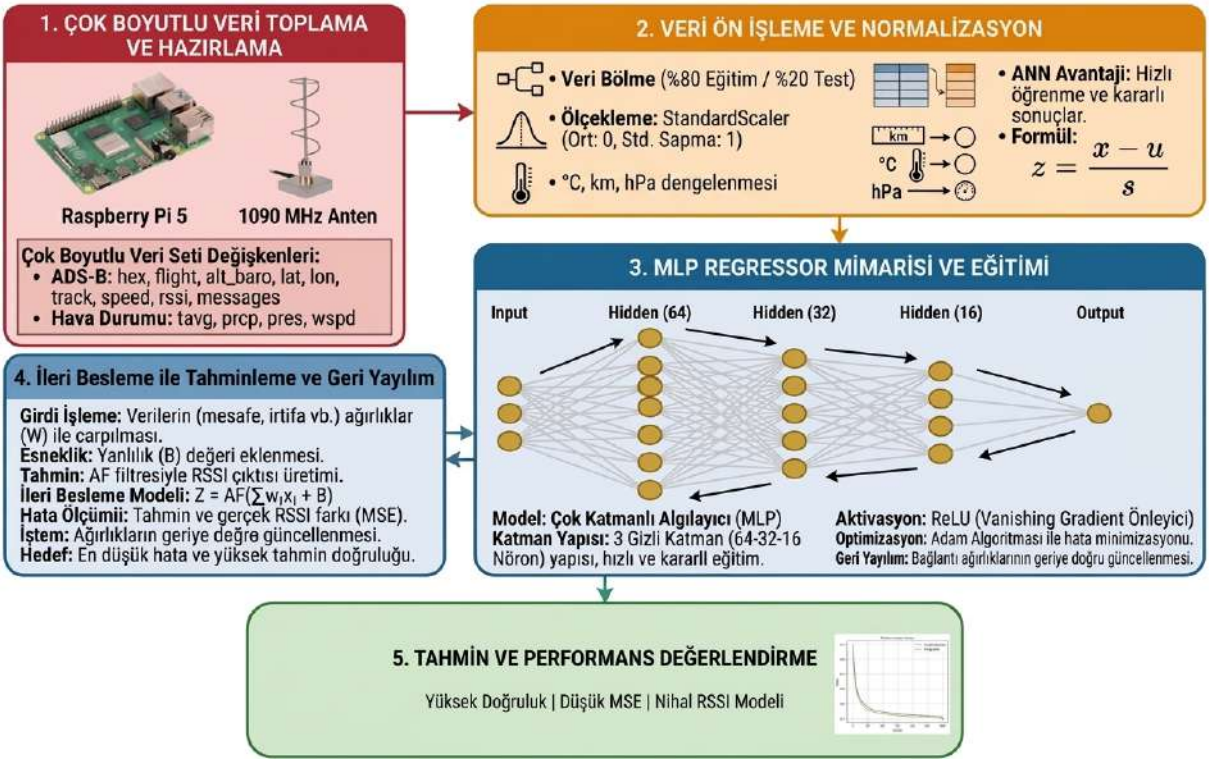
2. Yapay Sinir Ağları (Artificial Neural Networks – ANN)

Yapay Sinir Ağları, biyolojik insan beyninin çalışma ilkesinden ilham alınarak geliştirilmiş, paralel ve dağıtık yapıya sahip hesaplama modelleridir. Bir ANN, değişen ağırlık değerleriyle birbirine bağlanmış çok sayıda yapay nörondan oluşur. Her bir nöron, kendisine uygulanan girdi sinyallerini ağırlıklandırıp toplar ve bir aktivasyon fonksiyonu aracılığıyla bir çıktıya dönüştürür. Bu yapı, ağa karmaşık ve doğrusal olmayan ilişkileri modelleme yeteneği kazandırır. ANN'ler, özellikle matematiksel modelin açıkça tanımlanamadığı veya doğrusal olmayan süreçlerin incelendiği sistemlerde bilgi işleme amacıyla yaygın olarak kullanılmaktadır. Ağın öğrenme süreci; belirli bir kayıp fonksiyonunu minimize etmek amacıyla, başlangıçta rastgele atanan ağırlık ve yanlılık (bias) değerlerinin uygun öğrenme algoritmaları kullanılarak güncellenmesine dayanır. Bu öğrenme aşaması, ağ tasarımının en kritik evresidir. Ağın kararlı ve doğru sonuçlar üretmesi açısından büyük önem taşır. Yapay sinir ağlarının eğitilmesinde; gradyan inişli (gradient descent) geri yayılım (backpropagation) algoritması, genetik algoritmalar, Benzetimli Tavlama (Simulated Annealing), Hebbian öğrenmesi ve istatistiksel kestirim yöntemleri gibi çeşitli optimizasyon teknikleri yaygın olarak kullanılmaktadır. Doğrusal olmayan fonksiyon yakınsama kabiliyetleri sayesinde ANN'ler; sistem tanımlama, kontrol, optimizasyon, örüntü tanıma, sinyal işleme ve tahmin problemlerinde etkili çözümler sunmaktadır (Koyuncu, 2013).

Bu çalışmada, RSSI değerini tahmin etmek amacıyla ANN tabanlı bir regresyon yaklaşımı kullanılmıştır. Önerilen ANN yöntemi, yayılım ortamı parametreleri ile ölçülen RSSI değerleri arasındaki doğrusal olmayan ilişkiyi öğrenerek; farklı kanal ve ortam koşulları altında yüksek doğrulukta RSSI kestirimi sağlamayı amaçlamaktadır. Veriye dayalı bu yaklaşım, klasik analitik yayılım modellerinin yetersiz kaldığı durumlarda etkili bir alternatif sunabilir.

2.1 RSSI Tahmin Algoritması ve Uygulama Adımları

Bu çalışmada kullanılan yapay sinir ağı tabanlı tahmin yaklaşımı, veri toplama aşamasından sonuç değerlendirmesine kadar beş temel aşamadan oluşmaktadır. Bu aşamalar Şekil 2'de detaylı olarak açıklanmıştır.



Şekil 2. ANN Tahmin Algoritma Modeli

2.2 Çok Boyutlu Veri Toplama ve Hazırlama

1090 MHz ADS-B anteni ve bir Raspberry Pi aracılığıyla kurulan özgün bir yer istasyonundan elde edilen dinamik uçuş verileri (Mesafe, İrtifa, Hız vb.) yerel bir meteoroloji istasyonundan alınan atmosferik parametreler (Sıcaklık, Basınç, Yağış ve Rüzgâr) ile birleştirilerek homojen bir veri seti oluşturulmuştur. Öğrenme performansını artırmak amacıyla veriler, rastgele bir şekilde %80 eğitim seti ve %20 test seti olarak ikiye ayrılmıştır. Farklı birimlere (km, feet, °C, hPa) sahip veriler birimlerinden arındırılmış ve StandardScaler kullanılarak standart normal dağılıma dönüştürülmüştür. Scikit-learn kütüphanesinde yer alan StandardScaler, veri setindeki her bir özelliği, ortalaması sıfır (0) ve standart sapması bir (1) olacak şekilde dönüştürerek standart normal dağılıma getiren bir ön işleme aracıdır. Bu işlem, denklem 1'de gösterildiği gibi, veriden ortalamanın çıkarılması ve sonucun standart sapmaya bölünmesi ilkesine dayanmaktadır. Özellikle Yapay Sinir Ağları gibi algoritmalarda, farklı ölçeklerdeki verilerin birbirini baskılamasını önlemek ve daha hızlı, daha kararlı bir öğrenme süreci sağlamak amacıyla kullanılmaktadır (scikit-learn, 2026). StandardScaler formülündeki her bir değişkenin denklem 1'de açıklanmıştır:

$$\left(z = \frac{x-u}{s}\right) \quad (1)$$

z (Standart Skor / Z-Skoru): Hesaplama sonucunda elde edilen; ortalaması 0, standart sapması 1 olan yeni (ölçeklendirilmiş) veri değeridir.

x (Gözlemlenen Değer): Veri seti içerisindeki işlenmemiş, orijinal ham değerdir.

u (Ortalama): İlgili özelliğe (sütuna) ait tüm eğitim örneklerinin aritmetik ortalamasıdır.

s (Standart Sapma): Veri noktalarının ortalamadan ne kadar yayıldığını gösteren değerdir. Ölçeklendirme sırasında, birim varyans elde etmek amacıyla veriler bu değere bölünür (scikit-learn, 2026).

Bu işlem her bir özellik için bağımsız olarak hesaplanır, elde edilen istatistikler (ortalama ve sapma), daha sonra test verilerine aynı şekilde uygulanmak üzere model içerisinde saklanır.

2.3 MLPRegressor Mimarisi ve Hiperparametre Tanımlaması

ADS-B sinyal gücü (RSSI) ile çevresel değişkenler arasındaki doğrusal olmayan ve karmaşık ilişkileri analiz etmek amacıyla, üç gizli katmandan oluşan Çok Katmanlı Algılayıcı (Multilayer Perceptron-MLP) yapısı kullanılmıştır. Ağın derinliği; verideki yüksek boyutlu özelliklerin kademeli olarak işlenmesini sağlamak için sırasıyla 64, 32 ve 16 nöron içeren gizli katmanlarla yapılandırılmıştır. Gizli katmanların her birinde aktivasyon fonksiyonu olarak ReLU (Rectified Linear Unit) tercih edilmiştir. ReLU fonksiyonu, $f(x) = \max(0, x)$ hesaplamasını kullanarak ağa doğrusal olmayan özellikler kazandırırken, derin öğrenme modellerinde sıkça karşılaşılan kaybolan gradyan (vanishing gradient) problemini minimize eder; böylece eğitimin daha kararlı ve hızlı tamamlanmasına olanak tanır. Bu kapsamlı mimari yapı, Python'un scikit-learn kütüphanesi içerisindeki

$$MLPRegressor\left(hidden_{layer_{sizes}} = (64,32,16), activation =' relu'\right) \quad (2)$$

denklem 2 fonksiyonu kullanılarak uygulanmıştır (Pedregosa, 2018).

2.4 İleri Besleme ile Tahminleme (Forecasting with Forward Propagation)

Girdi katmanından alınan veriler (mesafe, irtifa vb.), sistemin öğrenme birimleri olan ağırlıklar (**ω**) ile çarpılarak önem sırasına göre derecelendirilir ve sisteme esneklik kazandırmak amacıyla bir yanlılık (***B***) değeri eklenir. Bu toplam, aktivasyon fonksiyonu olarak bilinen bir filtreden geçirilerek çıktı katmanında tahmin edilen RSSI değerine dönüştürülür (Unlersen, 2022).

$$Z = AF\left(\Sigma\omega ixi + B\right) \quad (3)$$

Yapay nöron yapısı içerisindeki değişkenlerin teknik tanımları denklem 3 aşağıda açıklanmıştır:

***xi* (Girdiler):** Modele giren ham verilerdir (örneğin; mesafe, irtifa).

***ωi* (Ağırlıklar):** Her bir girdinin nihai sonuç üzerindeki etkisini belirleyen katsayılardır. Önemli veriler daha yüksek bir ağırlıkla çarpılır.

***B* (Yanlılık / Bias):** Tahmin doğruluğunu ve sistem esnekliğini artırmak için modele eklenen matematiksel kaydırma (offset) değeridir.

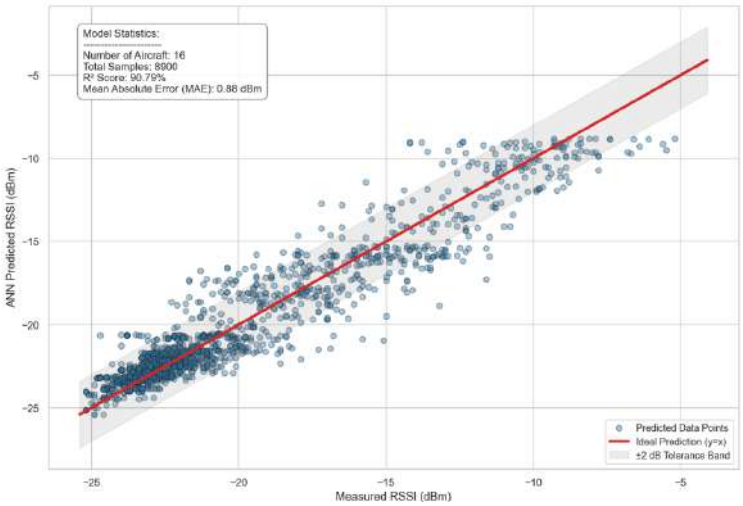
$\sum\omega ixi$ (Toplam Sembolü): Tüm girdilerin kendi ağırlıklarıyla çarpılıp toplandığı süreçtir; hücreye ulaşan toplam sinyal gücünü temsil eder.

***AF* (Aktivasyon Fonksiyonu):** Toplam sembolünden gelen değeri alır ve anlamlı bir çıktıya dönüştürür (örneğin; sonucu 0 ile 1 arasına sıkıştırmak gibi).

***Z* (Çıktı):** Hücre tarafından üretilen ve tahmin edilen RSSI değerini temsil eden sonuçtur.

2.5 Geri Yayılım ve Ağırlık Güncelleme (Backpropagation and Weight Updating)

Üretilen tahmin ile gerçek RSSI değeri arasındaki fark, Ortalama Kare Hata (MSE- Mean Squared Error) fonksiyonu kullanılarak hesaplanır. *Adam Optimizasyon* algoritması kullanılarak, hata payını minimize etmek amacıyla nöronlar arasındaki bağlantı ağırlıkları geriye doğru güncellenir. Modelin doğruluğu; daha önce hiç karşılaşmadığı %20'lik test seti üzerinde, Belirleyicilik Katsayısı (R^2) ve Ortalama Mutlak Hata (MAE- Mean Absolute Error) metrikleri kullanılarak değerlendirilmiştir. Elde edilen sonuçlar, Şekil 3'te regresyon grafiği aracılığıyla görselleştirilerek doğrulanmıştır.



Şekil 3. ANN-Tabanlı RSSI Tahmin Performansı

Şekil 3'te grafiğin merkezinden geçen kırmızı çizgi, $y = x$ (Mükemmel Doğruluk) doğrusunu temsil etmektedir. Eğer modelimiz hatasız olsaydı, tüm mavi veri noktaları tam olarak bu doğrunun üzerinde yer alırdı. Noktaların bu doğru etrafında oldukça dar bir koridor içerisinde kümelenmesi, modelin yüksek bir genelleme kabiliyetine sahip olduğunu kanıtlamaktadır. Kırmızı çizgiyi çevreleyen gri bölge, $\pm 2\,dB$ 'lik hata marjını temsil etmektedir. Görüldüğü üzere, 8.900 satır veri örneğinin büyük çoğunluğu bu gri bant içerisinde kalmaktadır. Bu durum; Yapay Sinir Ağları modelinin, ölçülen RSSI değerlerini %90,79 gibi yüksek bir R^2 skoru ve 0,88 dB gibi düşük bir Ortalama Mutlak Hata (MAE) ile doğru bir şekilde tahmin ettiğini kanıtlamaktadır.

2.6 İstatistiksel Başarı Metrikleri

Grafiğin sol üst köşesinde yer alan kutu, modelin performans karnesini temsil etmektedir:

R^2 (Belirleyicilik Katsayısı) = 0,9079: Bu değer, RSSI verilerindeki değişimlerin (varyansın) %90,79'unun modelimiz tarafından başarıyla açıklandığını göstermektedir. 0,90'ı aşan bir R^2 skoru, modelin verilerle son derece güçlü ve güvenilir bir uyum sağladığının göstergesidir.

MAE (Ortalama Mutlak Hata) = 0,8771 dB: Modelimiz, sinyal gücünü tahmin ederken 1 dB'den daha az (0,87 dB) bir ortalama sapma sergilemektedir. ADS-B sistemlerinde sinyal gürültüsü genellikle bu değerden daha yüksektir; dolayısıyla modelimiz, ortam gürültü tabanının (ambient noise floor) altında bir hata marjı ile çalışmaktadır. Yapılan analizler

sonucunda; 16 farklı uçaktan elde edilen verilerle eğitilen MLP tabanlı Yapay Sinir Ağı, karmaşık atmosferik koşullara rağmen ADS-B sinyal gücünü yüksek bir hassasiyetle başarıyla tahmin etmiştir. Elde edilen 0,87 dB'lik MAE değeri, önerilen modelin operasyonel havacılık emniyeti ve kapsama alanı planlaması için güvenilir bir temel oluşturduğunu kanıtlamaktadır.

3 Sonuç

Havacılık haberleşme sistemlerinin dijital ikizini oluşturmak ve operasyonel güvenliği artırmak için kritik bir araç olan RSSI tahmini, uçak tarafından gönderilen konum verilerini fiziksel sinyal gerçekliğiyle çapraz sorgulayarak sahte ADS-B sinyallerini (spoofing) anında tespit etmeyi sağlayabilir. Bu çalışmada, yerel bir istasyondan elde edilen gerçek zamanlı ADS-B verileri kullanılarak geliştirilen Yapay Sinir Ağları modelinin başarısı kanıtlanmış; Raspberry Pi 5 ve 1090 MHz anten donanımıyla toplanan konum, irtifa ve hava durumu gibi çok boyutlu parametreler, 64-32-16 nöron yapısındaki MLPRegressor mimarisine başarıyla entegre edilmiştir. Geleneksel yöntemlerle modellenmesi zor olan çevresel engellerin ve hava koşullarının sinyal üzerindeki etkisi, ReLU aktivasyon fonksiyonu ve Adam optimizasyonuyla desteklenen model sayesinde net bir şekilde analiz edilerek haberleşme kesintilerinin önüne geçilmiştir. Deneysel sonuçlar, modelin %90,79 gibi yüksek bir R^2 skoru ve 0,88 dBm gibi oldukça düşük bir ortalama mutlak hata (MAE) değeriyle çalıştığını göstererek, önerilen yöntemin havacılık veri analitiğinde ve uçuş güvenliği sistemlerinde yüksek doğruluklu bir kestirim aracı olduğunu ortaya koymuştur.

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SIGNAL ANALYSIS OF AUTOMATIC DEPENDENT SURVELLIENCE – BROADCAST (ADS-B) SYSTEM

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Abstract

The Automatic Dependent Surveillance-Broadcast (ADS-B) system is an advanced, rapidly expanding surveillance technology that operates in integration with satellite navigation systems to automatically broadcast an aircraft's position, identity, velocity, and other flight data. The aviation industry is evolving into a much more precise and efficient state by overcoming the limitations of traditional radar systems. By providing high-precision location data in real-time, the ADS-B system integrates with existing navigation surveillance technologies, making air traffic management safer and more traceable instantaneously. As a continuously evolving technology poised to replace traditional Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR), ADS-B not only enhances flight safety but also plays a crucial role in air traffic management, fuel consumption optimization, and enabling flight crews to monitor traffic more effectively. The ADS-B system obtains an aircraft's position, velocity, and vector data from Global Navigation Satellite System (GNSS) receivers and transmits these datasets to ground stations via either the 1090 MHz Mode S Extended Squitter (ES) or the 978 MHz Universal Access Transceiver (UAT) data links. The "ADS-B Out" component, which constitutes the fundamental element of the system, periodically broadcasts the aircraft's status data, while the "ADS-B In" function allows this data to be received by other aircraft, thereby enhancing the pilot's situational awareness in the cockpit. Compared to the scanning cycles of traditional radar systems, the update period for ADS-B data is significantly shorter. Thanks to this advanced technology, it has become possible to manage aircraft within vertical and horizontal separation limits. Within the scope of this study, the legal regulations regarding the ADS-B system are addressed. The general characteristics of Mode A and Mode C systems are specified. The technical structure of the Mode S system is examined in detail. Furthermore, the ADS-B message structure is explained, and Mode S transponder levels and technical capabilities are analysed. In addition, the structural decoding of ADS-B messages is exemplified, and methods for the collection and analysis of ADS-B data are presented.

Keywords: ADS-B, Mode S, Air Traffic Surveillance

OTOMATİK BAĞIMLI GÖZETİM – YAYIN (ADS-B) SİSTEMİNİN SİNYAL ANALİZİ

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Özet

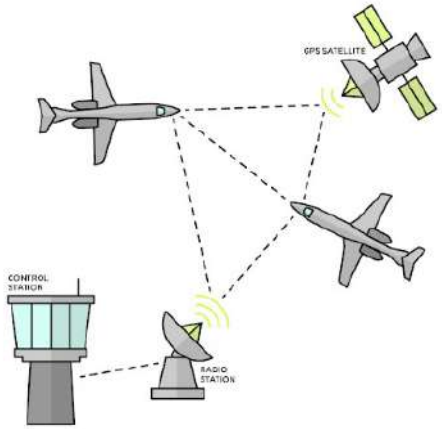
Otomatik Bağımlı Gözetim – Yayın (Automatic Dependent Surveillance-Broadcast, ADS-B) sistemi hava araçlarının konum, kimlik, hız ve diğer uçuş verilerini uydu seyrüsefer sistemleri ile entegre çalışır. Otomatik olarak yayınlayan, giderek kullanım alanları genişleyen gelişmiş bir gözetim teknolojisidir. Havacılık sektörü geleneksel radar sistemlerinin sınırlarını aşarak çok daha hassas ve verimli bir hale dönüşmektedir. Yüksek hassasiyetli konum verilerini gerçek zamanlı olarak sunan ADS-B sistemi, mevcut seyrüsefer gözetim teknolojileri ile bütünleşerek hava trafik yönetiminde daha güvenli ve anlık olarak izlenebilir bir duruma getirmiştir. Geleneksel birincil (Primary Surveillance Radar-PSR) ve ikincil gözetim (Secondary Surveillance Radar-SSR) radarlarının yerini almaya aday ve sürekli gelişmekte olan bu teknoloji uçuş emniyetini artırmakla kalmayıp, hava trafiğinin yönetiminde, yakıt tüketiminde ve uçuş ekibinin hava trafiğini daha etkin bir şekilde izlemesinde önemli rol oynamaktadır. ADS-B sistemi, hava aracının konum, hız ve vektör verilerini, Küresel Seyrüsefer Uydu Sistemi (Global Navigation Satellite System-GNSS) alıcılarından elde ederek, bu veri setlerini 1090 MHz Mode S ES Genişletilmiş Yayın (Extended Squitter) veya 978 MHz UAT Evrensel Erişim Alıcı-Vericisi (Universal Access Transceiver) veri bağlantıları üzerinden yer istasyonlarına iletir. Sistemin temel unsurunu teşkil eden 'ADS-B Out' bileşeni hava aracının durum verilerini periyodik olarak yayınlarken, 'ADS-B In' fonksiyonu bu verileri diğer hava araçları tarafından alınarak pilotun kokpitteki durumsal farkındalığını artırmasına olanak tanımaktadır. Geleneksel radar sistemlerinin tarama döngülerine kıyasla ADS-B verilerinin güncelleme periyodu daha kısadır. Bu gelişmiş teknoloji sayesinde, hava araçlarının dikey ve yatay doğrultuda birbirleri arasındaki mesafe limitleri içerisinde idare edilmesi mümkün olmuştur. Bu çalışma kapsamında, ADS-B sistemine ilişkin yasal mevzuat ele alınmıştır. Mode A ve Mode C sistemlerinin genel özellikleri belirtilmiştir. Mode S sisteminin teknik yapısı ayrıntılı biçimde incelenmiştir. Ayrıca, ADS-B mesaj yapısı açıklanmış, Mode S transponder seviyeleri ve teknik yetkinlikleri incelenmiştir. Buna ek olarak, ADS-B mesajlarının yapısal çözümlemesi örneklenmiş ve ADS-B verilerinin toplanması ile analizine yönelik yöntemler ortaya konulmuştur.

Anahtar Kelimeler: ADS-B, Mode S, Hava Trafik Gözetimi

1. Giriş

ADS-B sistemi, Hava Trafik Yönetiminde (ATM–Air Traffic Management) geleneksel radar teknolojisinden uydu tabanlı hassas konumlandırmaya geçişi temsil eden ileri düzey bir gözetim altyapısıdır. Temel çalışma ilkesi olarak hava araçlarının GPS (Global Positioning System) aracılığıyla elde ettikleri gerçek zamanlı ve yüksek doğruluktaki konum verilerini, yer istasyonlarına ve çevre trafik birimlerine periyodik olarak iletmesi esasına dayanmaktadır. Küresel ölçekte yeni nesil gözetim standardı olarak belirlenen bu teknoloji, Hava Trafik Kontrolörlerine (ATC–Air Traffic Controller) yüksek çözünürlüklü veri akışı sağlarken, pilotların durumsal farkındalığını kokpit içi trafik görüntüleme sistemleriyle doğrudan desteklemektedir. Operasyon emniyetini artırmasının yanında, hava sahası kapasitesinin optimizasyonu ve uçuş verimliliğinin azami düzeye getirilmesinde kritik bir rol oynayan ADS-B sistemi, gelecekte artırılmış veri kapasitesi ve ileri düzey havacılık uygulamalarıyla küresel hava trafiği modernizasyonunun temel yapısı olmaya devam edecektir.

ADS-B, uydu tabanlı bir gözetim teknolojisidir. Bu sistemde konum, hız ve kimlik bilgisi gibi kritik parametreler 1090 MHz Mode S ES (Extended Squitter) veri bağı aracılığıyla iletilmektedir. Günümüzde hava araçlarının büyük bir bölümü ADS-B mesajlarını sürekli olarak yayınlama kapasitesine sahiptir. 2020 yılı itibarıyla, Avrupa ve Amerika Birleşik Devletleri hava sahalarında operasyon gerçekleştiren sivil hava araçları için ADS-B uyumluluğu yasal bir zorunluluk haline getirilmiştir. Bu gereklilikleri karşılamayan eski nesil hava araçlarının ise belirlenen takvim çerçevesinde modernize edilmesi veya hizmet dışı bırakılması öngörülmektedir (Sun, 2021). Şekil 1'de ADS-B sisteminin temel gösterimi verilmiştir.



Şekil 1. ADS-B ağının şematik gösterimi (Wagenen, 2015)

2. ADS-B Gözetim Teknolojisi ve Yasal Çerçeve (FAA)

Federal Havacılık İdaresi bünyesindeki AFS-410 (Uçuş Teknolojileri ve Prosedürleri Grubu) tarafından yönetilen ADS-B sistemi, havacılık gözetim altyapısını geleneksel radar tabanlı yöntemlerden uydu tabanlı veri iletimine dönüştüren teknolojik bir yapıdır. ADS-B sistemi, uçağın konum, hız ve irtifa bilgilerini GPS aracılığıyla belirleyerek yer istasyonlarına ve çevre trafik birimlerine bir saniye aralıklarla yayınlaması esasına dayanmaktadır. Modern havacılık güvenliği ve verimliliğinin artırılmasını hedefleyen "NextGen" programının merkezinde yer alan bu teknoloji, operasyon standartlarını belirleyen yasal bir mevzuat çerçevesinde yürütülmektedir (FAAa, 2025). ADS-B sistemi fonksiyonel olarak iki ana bileşene ayrılmaktadır. "ADS-B Out", hava aracının seyrüsefer verilerini periyodik olarak dış dünyaya ileten temel fonksiyondur. 1 Ocak 2020 tarihinden itibaren "14 CFR § 91.225" (Codes of Regulation) Amerika Sivil Havacılık İdaresi maddesi uyarınca, kontrollü hava sahalarında operasyon yapan tüm hava araçları için zorunlu kılınmıştır. Ekipman performans standartları ise "14 CFR § 91.227" maddesi ile teknik olarak tanımlanmıştır (eCFR, 2026). "ADS-B In" ise hava aracının, çevredeki diğer trafik birimlerinden (TIS-B Traffic Information Service–Broadcast, Trafik Bilgi Hizmeti–Yayın) ve yer istasyonlarından gelen meteorolojik verileri (FIS-B Flight Information Services–Broadcast, Uçuş Bilgi Hizmetleri–Yayın) kokpit ekranına yansıtma kabiliyetidir (FAAb, 2023).

2.1 Stratejik ve Operasyonel Kazanımlar

ADS-B sisteminin havacılık endüstrisine entegrasyonu ile üç temel alanda stratejik avantaj sağlanmaktadır.

- **Hassasiyet ve Güvenlik**: Geleneksel radar sistemleri ancak 5 ila 12 saniyelik döngülerle veri güncelleyebilirken, ADS-B teknolojisi saniyede bir veri iletimi gerçekleştirir. Bu sürekli ve hızlı veri akışı sayesinde, hava araçları arasındaki dikey ve yatay emniyet mesafelerinin çok daha hassas şekilde optimize edilmesi sağlanmaktadır (ICAO, 2016).
- **Kapsama Alanı Genişletme**: Yer şekilleri veya coğrafi engeller nedeniyle radar sinyallerinin ulaşamadığı bölgelerde (dağlık alanlar, okyanus aşırı rotalar) kesintisiz gözetim sağlar.
- **Ekonomik ve Çevresel Verimlilik**: Uçuş rotalarının daha doğru izlenmesine imkân tanıyarak yakıt tüketimini ve karbon emisyonlarını azaltır.



Şekil 2. Otomatik Bağımlı Gözetim-Yayın Hava Sahası Kuralı (14 CFR § 91.225) Gösterimi Şekil (FAAc, 2025)

Şekil 2'te FAA'nın "14 CFR § 91.225" yönetmeliği uyarınca Amerika Birleşik Devletleri hava sahasında ADS-B Out ekipman zorunluluğunun coğrafi ve irtifa sınırlarını gösteren teknik şema şekildeki gibidir. Bu şekilde hava sahası dikey ve yatay bileşenlerine ayrılmıştır. Ekipman zorunluluğu üç ana kategoride incelemektedir (eCFR, 2026).

2.1.1 Yüksek İrtifa ve Kontrollü Hava Sahaları (Class A and E)

Class A Hava Sahası: 18.000 feet MSL (Mean Sea Level–Deniz Seviyesi) ile FL 600 (Hava Aracı İrtifası- Flight Level FL 600 = 60.000 feet) arasındaki bölgeyi kapsar. Bu sahada istisnasız 1090 Mhz ES transponder teknolojisi zorunludur.

Class E Hava Sahası: Kıta ABD'si (CONUS–Continental United State- ABD Ana Kara) üzerinde 10.000 feet MSL ve üzerindeki tüm hava sahasında ADS-B sistemi gereklidir. Ancak görselde belirtildiği üzere, yer seviyesinden (AGL-Aircraft Above Ground Level) 2500 feet yüksekliğe kadar olan bölge bu zorunluluktan muaf tutulmuştur (dağlık arazilerde düşük irtifa uçuşlarını desteklemek amacıyla düşünülmüştür).

2.1.2 Class B ve C Hava Sahaları

Şekil 2'de yoğun trafiğin olduğu havalimanı çevrelerini düğün pastası modeliyle oluşturulmuştur.

Class B: En büyük ve karmaşık hava sahasıdır. Yüzeyden 10000 feet MSL'ye kadar olan tüm katmanlarda ADS-B sistemi zorunludur. Ayrıca, ana havalimanı merkezli 30 deniz mili (30 NM) yarıçapındaki bölgeyi kapsayan "Mode C Veil" alanı içerisinde de (yüzeyden 10000 feet'e kadar) sistem kullanımı mecburidir.

Class C: Sınıf B'ye göre daha dar bir alanı kapsar. Yüzeyden 4000 feet AGL'ye (şemada genel sınır olarak 10000 MSL üst limiti belirtilmiştir) kadar olan hava sahasında ve bu sahanın üzerindeki 10000 feet MSL'ye kadar olan tüm hava sahalarında sistem ekipmanı gereklidir.

2.1.3 Kıyı ve Özel Limitler

Kıyı Şeridi: Meksika Körfezi gibi bölgelerde, kıyı çizgisinden 12 deniz mili (12 NM) açığa kadar olan ve 3000 feet MSL (veya belirli bölgelerde 10000 feet MSL) üzerindeki hava sahasında "ADS-B Out" zorunluluğu bulunmaktadır.

İstisnai Durumlar: Görselin sağ tarafında görülen dağlık arazide, 10000 feet MSL sınırının üzerinde olunsa dahi, eğer uçak yer seviyesinden AGL 2500 feet ve daha aşağıda seyrediyorsa ADS-B sistem gerekliliği ortadan kalkmaktadır. Sonuç olarak, pilotların ve operatörlerin hangi irtifa ve bölgede görünür olmaları gerektiğini belirleyen yasal bir navigasyon haritası niteliğindedir (FAAc, 2025).

3. Mode A/C Genel Tanıtımı

Mode A ve Mode C, SSR sisteminin ilk nesil standartlarını temsil eden ve Hava Trafiği Kontrol İşaret Sistemi (ATCRBS-Air Traffic Control Radar Beacon System) dahilinde kullanılan temel sorgulama modlarıdır. Mode A, uçağın kimliğini belirlemek amacıyla 4096 farklı oktal kod arasından atanan bir kimlik kodu (squawk code) iletimine dayanırken, Mode C ise uçağın barometrik irtifa bilgisini yer istasyonuna aktarmak için tasarlanmıştır. Ancak bu geleneksel modlar, tüm uçakların aynı frekans üzerinden yanıt vermesi nedeniyle yüksek trafik yoğunluğunda sinyal çakışması (synchronous garbling) ve hatalı yanıtlar (FRUIT- False Replies Unsynchronized In Time) gibi ciddi gözetim hatalarına yol açmaktadır (Sun, 2021). Sınırlı veri iletim kapasiteleri nedeniyle modern havacılık ihtiyaçlarını karşılamakta yetersiz kalmaktadır. Tablo 1'de Mode A, Mode C ve Mode S transponder kabiliyetleri özetlenmektedir.

Tablo 1. Transponder Modları Genel Gösterimi (Sun, 2021)

Mode A	Mode C	Mode S
Yalnızca tanımlama kodu (squawk code) gönderir	Mode A'nın gönderdiği tanımlama kodu ve irtifa bilgisini verir.	ICAO adresi (24-bit) tanımlama kodu
Bu kod, dört basamaklı oktal (0–7 arası) bir sayı olup 4096 farklı kombinasyon içerir.	İrtifa verisi, uçak içindeki kod çözücüden (altitude encoder) gelir ve ATC tarafından otomatik gösterilir.	İrtifa verisi, Veri bağlantısı (ADS-B, TCAS- (Traffic Alert and Collision Avoidance System))
ATC uçuşunuzun kimliğini bilir ancak irtifa bilgisi Mode A'da yoktur.	FAA'da sınırlı hava sahalarında (örneğin Mode C veil alanlarında) irtifa raporu zorunludur. (ATC, 2026)	ATC ve diğer uçaklarla seçici veri alışverişi yapabilir

4. Mode S Genel Tanıtımı

Mode S (Mode Select), geleneksel hava trafik kontrol radar sistemlerinin sinyal çakışması (synchronous garbling) ve hatalı yanıtlar (FRUIT) gibi kapasite sınırlamalarını aşmak amacıyla geliştirilmiş gelişmiş bir ikincil gözetim radarı (SSR) protokolüdür. Mode S'nin temel karakteristik özelliği, her uçağa atanan 24-bitlik benzersiz adresleme kabiliyeti sayesinde radarın uçakları seçici olarak sorgulayabilmesi (Selective Interrogation) ve bu yolla iletişim kanalı kapasitesini önemli ölçüde artırmasıdır. Sistemin kullandığı Genişletilmiş Yayın (Extended Squitter) (DF 17) formatı, ADS-B teknolojisinin temelini oluşturur. Bu yapı sayesinde uçaklar, yerden herhangi bir sorgu beklemeden kendi konum ve durum bilgilerini otomatik olarak yayınlar (Sun, 2021).

5. Mode S ve ADS-B Teknolojilerinin Entegrasyonu ve Teknik Analizi

Mode S Seçici Sorgulama, geleneksel ikincil radar (SSR) sistemlerinin yaşadığı sinyal çakışması (garbling) ve senkronize olmayan hatalı yanıtlar (FRUIT) gibi kapasite sınırlamalarını aşmak üzere geliştirilmiş bir gözetim protokolüdür. Mode S'in temel karakteristik özelliği, radarın her uçağa özel olarak atanan 24-bitlik transponder kodu sayesinde uçaklarla bireysel olarak iletişim kurabilmesidir. Bu sistem 2^{24} (yaklaşık 16,7 milyon) benzersiz adresi destekleyerek Mode A'daki kod kısıtlılığını ortadan kaldırmıştır. Sistem, sorgulama (uplink) için faz modülasyonunu, yanıt (downlink) için ise 1090 MHz frekansında Genlik Modülasyonu (PPM) tekniklerini kullanır. Genişletilmiş Yayın (ES), ADS-B verilerinin Mode S protokolü üzerinden aktarılmasını sağlayan temel mekanizmadır; bu doğrultuda DF 17, 18 ve 19 formatları ADS-B bilgilerinin taşınması için özel olarak yapılandırılmıştır. Geleneksel sistemlerin aksine ADS-B, uçağın konum, hız ve irtifa gibi kritik verilerini herhangi bir yer

istasyonu sorgusuna ihtiyaç duymadan periyodik olarak yayınlar. Sistemin "Genişletilmiş" (Extended) olarak adlandırılmasının sebebi ise standart Mode S mesajlarının 56 bitlik kapasitesini 112 bite çıkararak, çok daha karmaşık ve detaylı seyrüsefer verilerinin iletilmesine olanak tanımasıdır. Sonuç olarak Mode S, radar sistemleri için bir iletişim protokolü ve fiziksel taşıyıcı katman sağlarken, ADS-B bu altyapıyı özellikle DF 17 formatını kullanarak uydu tabanlı hassas gözetim verilerinin yayınlanmasını sağlar. Bu entegrasyon, radarın menzil ve doğruluk kısıtlarını ortadan kaldırarak modern hava trafik yönetiminin temelini oluşturmuştur (Sun, 2021).

5.1 ADS-B Mesaj Yapısı

Bir ADS-B mesajı 112-bit uzunluğundadır ve aşağıda Şekil 3'de gösterildiği gibi beş ana bölümden oluşmaktadır.



Şekil 3 ADS-B Mesaj Yapısı

Sivil hava araçlarına ait ADS-B mesajları, 'Downlink Format 17' ile başlamaktadır. Bu format, mesajın ilk 5 bitinde ikili sistemdeki 10001 değerine tekabül eder. 6. ve 8. bitler arasındaki bölüm transponder kapasitesini belirtirken, bu bölümü ICAO kodu olarak da bilinen 24 bitlik transponder adresi takip eder. Mesajın son iki kısmı ise 56 bitlik veri yükü ve 24 bitlik eşlik (parity) denetiminden oluşmaktadır.

Tablo 2. ADS-B Sinyal Yapısı

Bit	No. Bits	Kısaltma	Tanımlama
1–5	5	DF	Downlink Format
6–8	3	CA	Transponder kabiliyeti
9–32	24	ICAO	ICAO benzersiz adresi
33–88	56	ME	Mesaj
(33–37)	(5)	(TC)	(Tip Kodu)
89–112	24	PI	Parite/Sorgulayıcı Kimliği

Tablo 2'de ADS-B Mesaj yapısını detaylı bir şekilde açıklamaktadır. Mode S transponder kullanan hava araçları tarafından gönderilen ADS-B Genişletilmiş Yayın (ES) mesajları, Downlink Format 17 (DF=17) kullanılarak iletilir. Bu mesaj formatı, mesajın bir Mode S transponder üzerinden üretildiğini ve dolayısıyla ilgili hava aracının yer istasyonları veya diğer

sistemler tarafından sorgulanabilir olduğunu gösterir. Buna karşılık, transponder temelli olmayan ADS-B yayın sistemleri olan TIS-B verisini ileten ekipmanlar, Downlink Format 18 (DF=18) kullanarak veri gönderir. Bu tür sistemler, klasik Mode S transponder mantığıyla çalışmadıkları için harici sorgulamalara yanıt veremezler. DF=18 formatının kullanılması, bir ADS-B / TIS-B alıcı sistemi açısından kritik bir bilgidir. Alıcı sistem, mesajın DF=18 olduğunu tespit ettiğinde, bu yayının sorgulanamayan bir kaynaktan (örneğin yer tabanlı bir TIS-B istasyonu veya bağımsız bir ADS-B vericisi) geldiğini anlayabilir. Böylece alıcı sistem, mesajın kaynağını doğru şekilde sınıflandırır ve bu bilgiyi trafik izleme veya sinyal çakışma önleme algoritmalarında uygun biçimde kullanabilir. Özetle, DF=17 ve DF=18 arasındaki fark, yalnızca bir mesaj formatı farkı değil, aynı zamanda mesajı üreten sistemin yeteneklerini ve çalışma prensibini tanımlayan önemli bir ayırt edici özelliktir. Bu ayrım, ADS-B ve TIS-B tabanlı hava gözetim sistemlerinin güvenilir ve doğru çalışması açısından büyük önem taşır (Sun, 2021).

5.2 Mode S Transponder Seviyeleri ve Teknik Yetkinlikleri

Tablo 2'de gösterildiği gibi, Capability (CA), ADS-B mesajının ikinci alanıdır ve 3 bit uzunluğundadır. Bu 3 bitlik alan, mesajı gönderen Mode S transponder'ın yetenek seviyesini belirtir. Yani CA, bu mesajı gönderen transponder ne kadar gelişmiş olduğunu ve hangi durumda nasıl davranacağını açıklar. Mesaj 3 bit olduğu için alabileceği değerler, 000 → 111 (ikili sistem), oktal olarak ise 0 –7 arası değerlere karşılık gelir. Mode S transponder sistemleri, veri iletim kapasiteleri ve fonksiyonel yetkinliklerine göre farklı seviyelerde sınıflandırılmaktadır. Bu sınıflandırma, cihazın hangi veri paketlerini işleyebileceğini ve ADS-B protokollerini ne ölçüde desteklediğini belirler. Seviye 1 (Level 1): Yalnızca temel gözetim fonksiyonlarını yerine getiren, gelişmiş veri iletim yetenekleri kısıtlı olan cihazlardır. Seviye 2 ve Üzeri (Level 2+): ADS-B entegrasyonuna sahip, uçuş fazı ve durum bilgisi gibi karmaşık veri setlerini yönetebilen gelişmiş sistemlerdir (Sun, 2021).

5.3 Yetenek Alanı (Capability- CA) Parametrelerinin Analizi

ADS-B mesaj formatı içerisinde yer alan 3 bitlik CA (Capability) alanı, alıcı sistemlere (yer istasyonları veya diğer hava araçları) transponder'ın teknik kapasitesi ve uçağın operasyonel statüsü hakkında kritik bilgiler sunar. CA alanındaki değerlerin teknik karşılıkları aşağıda Tablo 3'de detaylandırılmıştır.

Tablo 3. Mode S transponder özelliği (CA)

CA Değeri	Teknik Tanımlama ve Operasyonel durum
0	Seviye 1 Transponder: Gelişmiş ADS-B fonksiyonlarını desteklemeyen, sınırlı yetkinliğe sahip eski nesil sistemleri ifade eder.
1-3	Rezerve (Reserved): Mevcut protokollerde tanımlanmamış olup, gelecekteki teknolojik güncellemeler için ayrılmıştır.
4	Seviye 2+ (Yer Statüsü): Gelişmiş yetkinliğe sahip uçağın yer sathında (on-ground) olduğunu ve CA=7 durumuna geçiş yapabildiğini belirtir.
5	Seviye 2+ (Hava Statüsü): Gelişmiş yetkinliğe sahip uçağın uçuş fazında (airborne) olduğunu ve CA=7 durumuna geçiş yeteneğini gösterir.
6	Seviye 2+ (Genel): Yer/hava ayrımı belirtmeksizin sistemin gelişmiş düzeyde olduğunu ve CA=7 tetikleme kapasitesine sahip olduğunu ifade eder.
7	Özel Durum Göstergesi: DR (Downlink Request) değerinin 0 olduğu veya uçuş statüsünün (FS: 2, 3, 4, 5) acil durum/özel operasyon bildirdiği öncelikli mesajları temsil eder.

Özetle Yetenek (CA) alanı, Mode S transponder'ın teknolojik hiyerarşisini, hava aracının dikey düzlemdeki operasyonel statüsünü ve iletilen mesajın teknik niteliği ile nasıl yorumlanması gerektiğini alıcı sistemlere bildiren stratejik bir göstergedir. Bu parametre vasıtasıyla, hava aracının yer veya hava fazında olduğu bilgisi anlık olarak doğrulanırken, aynı zamanda iletilen verinin güvenilirlik derecesi ve transponder'ın gelişmiş ADS-B fonksiyonlarını destekleme kapasitesi de teyit edilmektedir. Sonuç olarak CA alanı, hava trafik yönetiminde durumsal farkındalığın tesis edilmesi ve mesaj içeriğinin operasyonel önceliğinin belirlenmesi noktasında kritik bir işlev üstlenmektedir (Sun, 2021).

5.4 ICAO Adresi ve Hava Aracı Tanımlama Süreci

ADS-B mesaj yapısının en temel bileşenlerinden biri olan ICAO adresi, her bir hava aracının küresel ölçekte tekil olarak tanımlanmasını sağlayan bir parametredir. ICAO düzenlemeleri uyarınca Mode S transponder sistemlerine atanan bu kod, literatürde sıklıkla Mode S transponder kodu veya "hex code" olarak da adlandırılmaktadır. Teknik olarak bir ADS-B mesajının 9 ile 32. bitleri arasında (ikili sistemde) yer alan bu 24 bitlik alan, onaltılık gösterimde 3. ile 8. karakterler arasını kapsamaktadır. Her hava aracına özel ve benzersiz olarak atanan bu adres, dijital bir plaka işlevi görerek hava trafik yönetimi birimlerinin ve diğer hava araçlarının göndericiyi kesin olarak teşhis etmesine olanak tanır. Prensip olarak, bir hava aracına atanan ICAO adresi uçağın operasyon ömrü boyunca sabit kalacak şekilde tasarlanmıştır. Ancak teknik olarak transponder sisteminin yeniden programlanması mümkündür. Bu durum mesajların farklı bir adres altında yayınlanmasına yol açabilmektedir. Bu tür uygulamalar genellikle stratejik nedenlerle bazı askeri hava araçlarında veya gizlilik

protokolleri çerçevesinde FAA tarafından sunulan "Gizli ICAO Adres Sistemi" (PIA- Privacy ICAO Address) bünyesindeki özel jetlerde gözlemlenmektedir (Kendi FlightAware PiAware ADS-B Yer İstasyonunuzu kurmak ister misiniz?, 2026).

5.5 ADS-B Mesaj Türleri ve Tip Kodları (Type Codes)

Bir ADS-B mesajının hangi veri setini (konum, hız, kimlik vb.) taşıdığını belirlemek için mesaj yapısındaki Tip Kodu (Type Code) parametresinin analiz edilmesi gerekmektedir. Tip Kodu, 112 bitlik Mode S ES mesajının 33 ile 37. bitleri arasında yer alır. Bu bölüm aynı zamanda 56 bitlik ME segmentinin ilk 5 bitine denk gelir. Bu 5 bitlik veri alanı, $2^5 = 32$ farklı kombinasyon (0-31) sunarak mesajın içeriğini kategorize eder. Her bir Tip Kodu, ME segmentinin geri kalan 51 bitinin nasıl deşifre edileceğini tanımlar. Örneğin, uçağın havada ya da yerde oluşuna göre konum bilgisi farklı kodlarla iletilirken, uçağın çağrı adı (callsign) tamamen farklı bir kod kategorisinde yer alır. ADS-B Tip Kodları ile ME segmenti içerisindeki veri dağılımı arasındaki ilişki, aşağıdaki Tablo 4'te genel hatlarıyla verilmiştir. Tabloda mesajın tip kodu, mesajın içeriği ve genel açıklamalar bulunmaktadır (Sun, 2021).

Tablo 4. ADS-B Tip Kodu ve İçeriği

Tip Kodu (Type Code)	Mesajın İçeriği (Content)	Açıklama
1-4	Hava Aracı Tanımlama	Çağrı Adı (Callsign) ve kategori bilgisi
5-8	Yüzey Konumu (Surface Position)	Uçak yerdeyken iletilen konum ve hız verileri
9-18	Hava Konum (Airborne Position)	Barometrik irtifa ve GNSS tabanlı konum verileri
19	Hava Hızı (Airborne Velocity)	Yer hızı (Groundspeed) veya dikey hız verileri
20-22	Hava Konum (Yüksek Hassasiyet)	GNSS yüksekliği içeren gelişmiş konum mesajları
28	Operasyonel durum (Status)	Sistem kapasitesi ve operasyonel uyarılar
31	Operasyonel durum (Operational Satatus)	Mevcut operasyonel notlar ve yetenekler

6. ADS-B Mesajının Yapısal Çözümlemesi ve Uygulama Örneği

ADS-B protokolü, 112 bitlik bir veri paketinden oluşur ve bu paketin her segmenti belirli bir fonksiyonel göreve sahiptir. Örnek olarak ele alınan “8D4840D6202CC371C32CE0576098” ham verisi üzerinden mesajın bileşenlerini Tablo 5'te detaylandırabiliriz.

Mesaj Türü: Mesajın en başındaki 8D kodu, sistemin bu paketi nasıl okuyacağını belirler. Bu kodun içindeki ilk 5 bit bize 17 sayısını verir. Havacılık standartlarında "17", bu mesajın bir ADS-B mesajı olduğu anlamına gelir. Yani bu, uçağın yer istasyonundan soru beklemeden, kendi isteğiyle yayınladığı bir "genel yayın" paketidir.

Uçak Kimliği: 4840D6 adresi, bu uçağın dünya üzerindeki benzersiz ICAO kodudur.

İçerik Türü: ME alanının başındaki 4 (Type Code 4) bu mesajın uçağın koordinatlarını değil, ismini/çağrı adını bildirdiğini gösterir. **Not**: 4 (Type Code), mesajın ME (Message Data) dediğimiz ana yük (payload) kısmının en başında bulunur. Bu mesaj parçalara ayrıldığında ME (Message Data) kısmı şudur: 202CC371C32CE0. Bu ME alanının en başındaki ilk karakter olan "2" (onaltılık sistemde), ikilik sisteme (binary) çevrildiğinde Type Code'u belirler (Sun, 2021).

- ✓ ME Alanı: 202CC371C32CE0
- ✓ İlk Byte (8 bit): 20
- ✓ Type Code (İlk 5 bit): 20 onaltılık (hex) değeri ikilik sistemde “00100 0000” şeklindedir. Buradaki ilk 5 bit olan “00100”, onluk (decimal) sistemde 4 rakamına eşittir

  Özetle “20 hex → 00100000 binary → İlk 5 bit: 00100 → 4 decimal”

Tablo 5. ADS-B Mesajı Yapısal Çözümleme (Sun, 2021).

Bölüm	Kısaltma	Tanım	Dğer (Hex)	Değer (Binary)	Değer (Decimal)
Downlink Format	DF	Mesaj Türü (17=ADS-B)	8D (İlk 5 bit)	10001	17
Capability	CA	Operasyonel Yetenek	8D (Son 3 bit)	101	5
ICAO Address	ICAO	Hava Aracının benzersiz kimliği	4840D6	0100 1000 0100 0000 1101 0110	4 735 190
Message Data	ME	Yük (Payload)	202CC371C32CE0	0010 0000 0010 1100 1100 0011 0111 0001 1100 0011 0010	9 035 110 917 160 160

				1100 1110 0000	
Parity/Interrogator	PI	Hata kontrolörü (CRC)	576098	0101 0111 0110 0000 1001 1000	5726360

6.1 Mesaj Erişilebilirliği ve İletim Oranları

Farklı ADS-B mesaj türleri, bant genişliğini optimize etmek ve hava trafik yönetimine en kritik veriyi en hızlı şekilde sunmak amacıyla farklı iletim oranlarına sahiptir. Güncelleme sıklığı, hava aracının havada veya yerde olmasına, yerdeyken sabit veya hareketli durumda bulunmasına göre dinamik olarak değişmektedir. Tablo 6, ADS-B Versiyon 2 standartlarına göre temel mesajların iletim hızlarını özetlemektedir (Sun, 2021).

Tablo 6. ADS-B mesaj iletim hızları ADS-B Versiyon 2 (Sun, 2021).

Mesaj Türü	Tip Kodları (TC)	Yer (Sabit)	Yer (Hareketli)	Havada
Hava Aracı Tanımlama	1-4	0.1Hz	0.2Hz	0.2Hz
Yüzey Konumu	5-8	0.2 Hz	2Hz	-
Havada Konum	9-18, 20-22	-	-	2Hz
Havada Hız	19	-	-	2Hz
Hava Aracı Durumu	28	0.2Hz*	0.2Hz*	1.25Hz**
Hedef Durum ve Statüsü	29	-	-	0.8 Hz
Operasyonel Durum	31	0.2Hz	0.4 Hz***	1.13 Hz****

*TCAS RA (Traffic Collision Avoidance System Resolution Advisory- Trafik Çarpışma Önleme Sistemi Karar Tavsiyesi) veya Squawk kodu (transponder tarafından yayınlanan dört haneli tanımlayıcı kod) değişmediğinde, ADS-B mesaj gönderim hızı sabit kalır.

** TCAS RA veya Tanımlama Kodu değişirse, bu durum uçuş güvenliği açısından önemli kabul edilir ve ADS-B veri gönderim hızı artar.

*** NIC/NIL/SIL parametrelerinde değişim olmadığı durumlarda.

**** NIC/NAC/SIL parametrelerinde değişim durumunda hız artar.

NIC (Navigation Integrity Category-Seyrüsefer Bütünlük Kategorisi), NAC (Navigation Accuracy Category - Seyrüsefer Doğruluk Kategorisi), SIL (Source Integrity Level- Kaynak Bütünlük Seviyesi)

6.2 ADS-B Versiyon 0'dan Versiyon 1'e Geçiş ve Yapısal İnovasyonlar

ADS-B teknolojisinin evriminde Versiyon 1, yeni mesaj türlerinin sisteme dahil edilmesi ve belirsizlik göstergelerinin daha hassas bütünlük göstergeleriyle değiştirilmesi açısından kritik bir dönüm noktasıdır. Versiyon 1 ile birlikte hayata geçirilen temel teknik değişiklikler aşağıda maddeler halinde sunulmuştur.

- Yeni Mesaj Türlerinin Eklenmesi ile sisteme tip kodu (TC) 28 ve 31 olan yeni mesaj formatları dahil edilmiştir.
- TC=28 (Hava Aracı Durumu): Bu mesaj tipi; acil durum/öncelik statülerini ve ACAS (Airborne Collision Avoidance System- Havadan Çarpışma Önleme Sistemi) Çözünürlük Önerisi (RA- Resolution Advisory) yayınlarını içermektedir.
- TC=31 (Operasyonel Durum) Hava aracının mevcut operasyonel yeteneklerini ve sistem modlarını raporlamak için kullanılmaktadır.
- Güvenilirlik Parametrelerinin Yenilenmesi: Eski nesil Navigasyonel Belirsizlik Kategorileri (NUC- Navigation Accuracy Category- Konum doğruluğunu belirtir) sistemden kaldırılmıştır. Bunun yerine, verinin doğruluğunu ve güvenilirliğini çok daha hassas tanımlayan Navigasyon Bütünlük Kategorisi (NIC- Navigation Integrity Category-Seyrüsefer Bütünlük Kategorisi) ve Gözetim Bütünlük Seviyesi (SIL- Source Integrity Level- Kaynak Bütünlük Seviyesi) parametreleri tanıtılmıştır.
- NIC Parametresinin Tanımlanması: NIC değerinin belirlenmesinde hem Tip Kodu (TC) hem de yeni eklenen bir parametre olan NIC Destek Biti (NICs) birlikte kullanılmaktadır.
- Operasyonel Durum Mesajı (TC=31) Güncellemeleri: NIC Destek Biti (NICs) artık operasyonel durum mesajlarının (TC=31) içerisinde yer almaktadır. Ayrıca, hava aracının hangi ADS-B versiyonunu kullandığı bilgisi de bu mesaj türü üzerinden iletilmektedir (Sun, 2021).

6.3 ADS-B Versiyon 1'den Versiyon 2'ye Geçiş ve Hassasiyet Artışı

ADS-B teknolojisinin en modern evresi olan Versiyon 2, Versiyon 1'de temelleri atılan bütünlük kategorilerini daha rafine hale getirerek hava trafik yönetiminde emniyet standartlarını en üst seviyeye taşımıştır. Bu versiyonla birlikte hayata geçirilen temel yapısal ve fonksiyonel değişiklikler şunlardır.

- Mesaj Yapılarının Yeniden Tanımlanması, TC=28 (Hava Aracı Durumu) ve TC=31 (Operasyonel Durum) mesajlarının hem içeriği hem de veri yapısı, operasyonel ihtiyaçlara göre yeniden düzenlenmiştir.
- Gelişmiş Bütünlük Göstergeleri (NIC Supplement Bits), Navigasyon bütünlüğünü daha dar hata payları ile tanımlayabilmek adına üç yeni destek biti sisteme dahil edilmiştir:
  - ✓ NICa: Operasyonel durum mesajları (TC=31) içinde tanımlanmıştır.
  - ✓ NICb: Havada konum mesajları (TC=9–18) içinde tanımlanmıştır.
  - ✓ NICc: Operasyonel durum mesajları (TC=31) içinde tanımlanmıştır.
- Yatay Sınırlama Yarıçapı (Rc) Güncellemesi: Havada konum mesajlarının TC=13 kodlu segmentinde, NIC=6 seviyesi içerisinde ek bir Yatay Sınırlama Yarıçapı (Rc- Horizontal Containment Radius) seviyesi tanımlanmıştır. Bu sayede, hava aracının pozisyonel hata payı çok daha spesifik sınırlarla raporlanabilmektedir.

Özet olarak Versiyon 2 ile gelen bu yenilikler, sistemin sadece nerede olduğunu değil, bu bilginin ne kadar kesin olduğunu da milimetrik bir doğrulukla iletmesini sağlar. Özellikle NICa, NICb ve NICc bitlerinin farklı mesaj tiplerine yayılması, alıcı sistemlerin uçağın konumu üzerindeki güven sınırını (integrity bound) her an denetleyebilmesine olanak tanır. ADS-B sisteminde kullanılan versiyonun doğru tespit edilmesi, mesaj içeriklerinin (özellikle TC=28 ve TC=31) hatasız deşifre edilmesi için kritik bir öneme sahiptir. Versiyon 0 ile sonraki sürümler arasındaki en temel fark, Versiyon 0'ın kendi sürüm bilgisini herhangi bir mesaj içerisinde barındırmamasıdır. Bu durum, hava aracının hangi ADS-B versiyonunu kullandığını belirlemek için iki aşamalı bir kontrol sürecini zorunlu kılar (Sun, 2021).

6.4 ADS-B Versiyonu Tespit Süreci

Operasyonel Durum Mesajı (TC=31) Kontrolü, ilk aşamada hava aracının TC=31 (Operational Status) tip koduna sahip bir mesaj yayınlayıp yayınlamadığı denetlenir. Eğer belirli bir gözlem süresi boyunca bu tip kodunda hiçbir mesaj raporlanmazsa, söz konusu hava aracının Versiyon 0 kullandığı varsayılır. Sürüm Numarası Analizi, eğer TC=31 tip kodlu mesajlar alınıyorsa, mesajın içindeki spesifik bit alanları incelenir. Versiyon numarası bilgisi, ME segmentinin 41–43. bitleri arasında (tüm mesaj yapısında ise 73–75. bitlerde) yer almaktadır. Bu alandaki değer, sistemin Versiyon 1 mi yoksa Versiyon 2 mi olduğunu kesin olarak tanımlar (Sun, 2021).

6.5 Veri İşleme ve Deşifre Stratejisi

Hava aracının ADS-B versiyonu bir kez doğru şekilde tanımlandıktan sonra (bu bilgi operasyonel süreçte nadiren değişir), ilgili hava aracından gelen tüm TC=28 ve TC=31 mesajları bu versiyonun protokol standartlarına göre deşifre edilebilir. Bu ayrım özellikle şunlar için gereklidir. Hata Payı Analizi, Versiyon 1 ve 2'deki NIC/SIL gibi bütünlük değerlerinin doğru yorumlanması, Acil Durum Bildirimleri, TC=28 içindeki ACAS/TCAS verilerinin doğru işlenmesi (Sun, 2021).

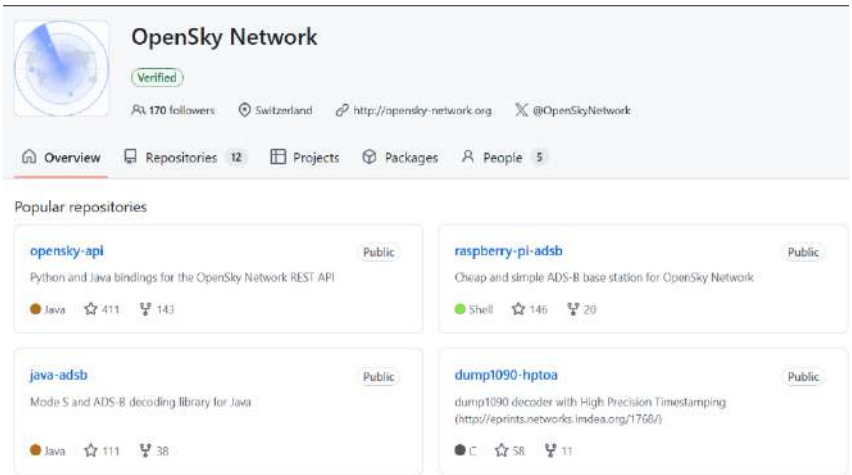
7. ADS-B Veri Toplama ve Analizi

ADS-B sisteminin şifrelenmemiş ve tek yönlü yayın yapısı sayesinde, bireysel kullanıcılar temel donanımlar kullanarak basit bir ADS-B alıcı istasyonu kurabilir ve hava araçlarının yayınladığı konum, hız, irtifa ve kimlik bilgilerini pasif olarak toplayabilir. Bu veriler, Python ve MATLAB gibi bilimsel hesaplama ortamlarında işlenerek hava trafik yoğunluğu analizi, uçuş rotalarının istatistiksel incelenmesi ve operasyonel eğilimlerin ortaya çıkarılması gibi akademik çalışmalarda kullanılabilir. Python tarafında NumPy, Pandas ve SciPy veri işleme ve istatistiksel analiz için, Matplotlib, Seaborn ve Plotly görselleştirme için, pyModeS, dump1090 çıktıları ve OpenSky API entegrasyonu ise ADS-B mesajlarının çözümü ve zenginleştirilmesi için yaygın olarak kullanılmaktadır. MATLAB ortamında ise Aerospace Toolbox, Mapping Toolbox ve yerleşik veri analiz fonksiyonları aracılığıyla uçuş verileri modellenebilmekte, filtreleme ve zaman serisi analizleri gerçekleştirilebilmektedir. Bu yaklaşımlar, ADS-B verilerinin akademik olarak anlamlandırılmasını ve veri temelli sonuçlar üretilmesini mümkün kılmaktadır.



Şekil 4. Basit ADS-B Alıcı İstasyonu, (Kendi FlightAware PiAware ADS-B Yer İstasyonunuzu kurmak ister misiniz)

OpenSky API ve benzeri GitHub tabanlı havacılık API'leri, küresel ölçekte dağıtılmış ADS-B alıcı ağlarından elde edilen gerçek zamanlı ve tarihsel hava trafik verilerine yazılım tabanlı erişim sağlayan ara yüzlerdir. Bu sistemler, uçakların konumu, hızı, irtifası, yönü ve tanımlayıcı bilgileri gibi temel uçuş parametrelerini sunarak hava trafik akışının analizi, uçuş performansının değerlendirilmesi, emniyet ve çarpışma riski çalışmaları, hava trafik yönetimi (ATM) sistemlerinin doğrulanması ile ADS-B tabanlı gözetim teknolojilerinin incelenmesine olanak tanır. Dolayısıyla bu API'ler, havacılık alanında veri odaklı akademik araştırmalar, simülasyon çalışmaları ve karar destek sistemlerinin geliştirilmesi için güvenilir ve açık bir veri kaynağı niteliği taşımaktadır.



Şekil 5. Open Sky Network, (Open Sky Network, 2026)

8. Sonuç

Bu çalışmada, ADS-B ve Mode S tabanlı gözetim sistemleri hem teorik hem de uygulama perspektifinden kapsamlı biçimde ele alınmıştır. ADS-B teknolojisinin, klasik radar tabanlı sistemlerden farklı olarak sürekli ve otomatik veri yayınına dayanması, modern hava trafik yönetiminde önemli bir paradigma değişimi yarattığını göstermektedir. Bu bağlamda, ADS-B'nin konum, hız ve kimlik gibi kritik uçuş parametrelerini doğrudan yayınlaması, gözetim doğruluğunu ve operasyonel farkındalığı artırmaktadır. Çalışmada incelenen Mode S sistemi ise seçici sorgulama (selective interrogation) yeteneği ve 24 bitlik benzersiz ICAO adresleme yapısı sayesinde, önceki Mode A/C sistemlerine kıyasla daha yüksek kapasite ve daha güvenilir veri iletimi sağlamaktadır. Ayrıca Mode S mesajlarının 56 ve 112 bitlik standart yapılara sahip olması ve hata tespiti için CRC (Cyclic Redundancy Check- Döngüsel Artıklık Denetimi) tabanlı parite mekanizmalarının kullanılması, sistemin veri bütünlüğü açısından güçlü bir mimariye sahip olduğunu ortaya koymaktadır. ADS-B ile Mode S entegrasyonu değerlendirildiğinde, her iki sistemin 1090 MHz frekansı üzerinden çalışması ve aynı fiziksel altyapıyı paylaşması, veri erişimini kolaylaştıran ve düşük maliyetli çözümlerle analiz yapılmasına imkân tanıyan önemli bir avantaj sunmaktadır. Bununla birlikte, ADS-B'nin sorgu gerektirmeden sürekli yayın yapması, klasik SSR yapısından farklı olarak daha esnek ve ölçeklenebilir bir gözetim yaklaşımı sağlamaktadır.

Sonuç olarak, bu araştırma kapsamında gerçekleştirilen teknik analizler, mesaj yapısı çözümlemeleri ve veri işleme yaklaşımları; ADS-B ve Mode S sistemlerinin yalnızca mevcut hava trafik yönetiminde değil, aynı zamanda veri odaklı gelecekteki hava ulaşım sistemlerinde de kritik bir rol oynayacağını göstermektedir.

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INVESTIGATION OF THE CONTROL POTENTIAL OF MICROBIAL FERTILIZERS AGAINST TOMATO BACTERIAL CANKER AND WILT DISEASE

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Abstract

In this study, the effect of different microbial fertilizers against tomato bacterial canker and wilt disease was investigated. The microbial fertilizers RhizoFill (*Bacillus subtilis*, *B. megaterium*, *Pseudomonas fluorescens*) and Subtima (*B. subtilis*), supplied by NG-Biyoteknoloji Ltd. Şti., the Cmm-PK-1 isolate identified as *Clavibacter michiganensis* subsp. *michiganensis* (*Cmm*) through biochemical tests and molecular analysis (PCR) isolated from the vascular bundles of tomato plants, and tomato seedlings of the Alsancak F1 variety were used. Two different doses of each microbial fertilizer, 250 cc and 500 cc, were applied. In the experiment conducted in a climate chamber, a total of five microbial fertilizer applications were performed: before pathogen inoculation, during inoculation, and after inoculation. Pathogen inoculation was carried out 10 days after transplanting the seedlings. A *Cmm* suspension prepared from pure cultures and adjusted to a density of 1×10^6 cells mL^{-1} using a spectrophotometer was applied under the stem bark with a sterile syringe. NC plants that did not receive microbial fertilizer were treated with sterile water, while PC plants were inoculated only with the pathogen. Disease severity in the plants was evaluated according to a 0–5 scale, and pathogen spread was also determined by measuring lesion lengths in the vascular bundles through longitudinal sections of the stem. According to the evaluations, disease severity in PC plants was determined as 2.25, while the lesion length formed in the vascular bundles was measured as 13.88 cm. Compared to PK, disease severity in the 250 cc dose of the microbial fertilizer RhizoFill was determined as 1.80, and the lesion in the vascular bundles was measured as 12.30 cm. With the increase in dose (P1-500), a decrease in disease severity and lesion length was observed, with disease severity dropping to 1.60 and the lesion to 10.66 cm. Subtima showed a higher effect compared to RhizoFill. The lowest disease severity (0.87) and the lowest lesion length (5,84 cm) were observed with the 500 cc dose of Subtima. In conclusion, this study has demonstrated that the microbial fertilizers RhizoFill and Subtima, which have a positive effect on plant growth, possess biocontrol potential against tomato bacterial canker and wilt disease. The conducted study is of a preliminary nature, and it is necessary to demonstrate the disease suppression properties of microbial fertilizers in greenhouse and field studies as well.

Keywords: *Clavibacter michiganensis* subsp. *michiganensis*, microbial fertilizer, biological control, tomato.

MİKROBİYAL GÜBRELERİN DOMATES BAKTERİYEL KANSER VE SOLGUNLUK HASTALIĞINA KARŞI MÜCADELE POTANSİYELLERİNİN ARAŞTIRILMASI

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Özet

Bu çalışmada farklı mikrobiyal gübrelerin domates bakteriyel kanser ve solgunluk hastalığına karşı etkisi araştırılmıştır. Çalışmada NG-Biyoteknoloji Ltd. Şti. tarafından temin edilen RhizoFill (*Bacillus subtilis*, *B. megaterium*, *Pseudomonas fluorescens*) ve Subtima (*B. subtilis*) mikrobiyal gübreleri, domates bitkisinin iletim demetlerinden izole edilen biyokimyasal testler ve moleküler analiz (PCR) ile *Clavibacter michiganensis* subsp. *michiganensis* (*Cmm*) olarak tanılanan Cmm-PK-1 izolatı ve Alsancak F1 çeşidine ait domates fideleri kullanılmıştır. Her iki mikrobiyal gübrenin 250 ve 500 cc olmak üzere iki farklı dozu kullanılmıştır. İklim odasında yürütülen denemede patojen inokülasyonu öncesi, inokülasyon esnasında ve inokulasyondan sonra olmak üzere toplam beş mikrobiyal gübre uygulaması gerçekleştirilmiştir. Patojen inokulasyonu, fidelerin şaşırtılmasından 10 gün sonra gerçekleştirilmiştir. Saf kültürlerden hazırlanan ve spektrofotometrede yoğunluğu 1×10^6 hücre mL^{-1}'e ayarlanan *Cmm* süspansiyonu steril bir enjektör yardımıyla gövde kabuk altına uygulanmıştır. Mikrobiyal gübre uygulanmayan NK bitkilerine saf su, PK bitkilerine ise sadece patojen inoküle edilmiştir. Bitkilerdeki hastalık şiddeti 0–5 skalasına göre değerlendirilmiş, ayrıca gövdenin boyuna kesiti ile iletim demetlerindeki lezyon uzunlukları ölçülerek patojen yayılımı da belirlenmiştir. Yapılan değerlendirmelerde PK bitkilerinde hastalık şiddeti 2,25 olarak belirlenirken, iletim demetlerinde oluşan lezyon uzunluğu 13,88 cm olarak ölçülmüştür. PK ile kıyaslanan mikrobiyal gübrelerden RhizoFill 'in 250 cc'lik dozunda hastalık şiddeti 1,80 olarak belirlenmiş olup, iletim demetlerindeki lezyon 12,30 cm olarak ölçülmüştür. Doz artışı ile birlikte (P1-500) hastalık şiddetinde ve lezyon uzunluğunda azalma gözlenmiş olup hastalık şiddeti 1,60'a, lezyon 10,66 cm'ye düşmüştür. Subtima ise RhizoFill'e kıyasla daha yüksek etki göstermiştir. En düşük hastalık şiddeti (0,87) ve en düşük lezyon uzunluğu (5,84 cm) Subtima 500 cc'lik dozunda görülmüştür. Sonuç olarak, bitki gelişimi üzerinde olumlu etki yapan RhizoFill ve Subtima mikrobiyal gübrelerinin domates bakteriyel kanser ve solgunluk hastalığına karşı biyokontrol potansiyeline sahip olduğu yapılan bu çalışma ile ortaya konmuştur. Yapılan çalışma bir ön çalışma niteliğinde olup, sera ve arazi çalışmaları ile mikrobiyal gübrelerin hastalık baskılama özelliklerinin bu alanlarda da ortaya konulması gerekmektedir.

Anahtar Kelimeler: *Clavibacter michiganensis* subsp. *michiganensis*, mikrobiyal gübre, biyolojik mücadele, domates.

1. Introduction

Tomato (*Solanum lycopersicum* L.*)* belongs to the nightshade family (*Solanaceae*) and is a widely cultivated agricultural product with high economic value worldwide (Panno et al., 2021). Although botanically classified as a fruit, it is considered a vegetable in agricultural production and trade. Besides being consumed fresh, it is processed into various forms such as tomato paste, sauces, and ketchup (Al-Remi et al., 2018). According to FAO (2024) data, tomato production in Türkiye is approximately 13.3 million tons, ranking third after China and India. Tomato production in Türkiye is carried out both under cover and in open fields, and is concentrated especially in Antalya, Mersin and the Aegean-Marmara Regions.

In tomatoes grown both in open fields and under cover worldwide, crop losses occur due to bacterial, fungal, and viral pathogens. In tomato cultivation, several fungal pathogens, such as early blight (*Alternaria solani* (Ellis & Martin) Sorauer) (Schmey et al., 2024), late blight (*Phytophthora infestans* (Mont.) de Bary) (Singh et al., 2025), Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) Snyder & Hansen) (Tunabaş and Erkılıç, 2022), grey mold (*Botrytis cinerea* Pers.) (Haşım et al., 2020), and Septoria leaf spot (*Septoria lycopersici* Speg.), as well as viral agents like Tomato yellow leaf curl virus, Tomato brown rugose fruit virus (Panno et al., 2021), and Tomato spotted wilt virus, cause significant crop losses. Among the bacterial agents, *Clavibacter michiganensis* subsp. *michiganensis* [(Smith) Davis et al.] causes Tomato Bacterial Canker and Wilt Disease. *C. michiganensis* subsp. *michiganensis* is one of the most important bacterial agents limiting tomato production worldwide. First discovered in the United States in 1909, it has been reported in every region where tomato is grown (EPPO, 2026). Although it varies from region to region, it can cause crop losses of up to 80% (Çetinkaya-Yıldız et al., 2018). Although the pathogen causes disease in plants such as eggplant and pepper in the *Solanaceae* family, it causes the most significant economic loss in tomatoes. It negatively affects tomato production in both greenhouse and open fields. Tomato plants are particularly susceptible to the disease in their young stage. Disease symptoms vary depending on the route of entry of the pathogen into the plant. If the infection develops from the seed or if the pathogen enters the vascular bundles directly through open wounds, systemic infection occurs; if the pathogen enters the plant through natural openings such as hydathodes or wounds caused by broken hairs, localized infection occurs. The typical disease symptom in systemic infection is unilateral wilting or discoloration. As the disease progresses, cracks and wounds

occur in the bark of the branches. This condition is called bacterial canker. The spots that form on the fruits are called bird's eye spots (Çetinkaya-Yıldız et al., 2018).

Chemical and cultural methods have been used to combat the disease for many years, but these methods generally provide limited solutions. Therefore, it is necessary to develop environmentally friendly and sustainable control approaches. In recent years, biological fertilizers (microbial fertilizers) containing microorganisms that promote plant growth and exhibit disease suppressive effects have come to the forefront among environmentally compatible alternatives (El-Saadony et al., 2022). Microbial fertilizer is a type of biological fertilizer that has gained increasing importance in agriculture in recent years, supporting plant growth and increasing soil fertility. These biological products, containing beneficial microorganisms such as *Bacillus, Pseudomonas*, and *Paenibacillus*, support nutrient uptake by the plant, increase resistance to diseases, and exhibit pathogen-suppressing effects (Anonymous, 2026a). In this context, they can be effective against diseases through multifaceted mechanisms such as antibiotic production, siderophore synthesis, and the secretion of cell wall-degrading enzymes (Kloepper et al., 2004).

Chemical applications aimed at rapid control can disrupt the biological balance in the soil, negatively impact the ecosystem, and cause salinization and acidification. Microbial fertilizers, which stand out as an environmentally friendly agricultural practice, improve soil structure and support plant health. Numerous studies in the literature focus on biological control and the application of various beneficial microorganisms (Akgül and Mirik, 2008; Wang et al., 2021; El Saadony et al., 2022; Abdelaziz et al., 2023; El hjouji et al., 2025). In this context, some studies showing that microbial fertilizers support plant growth (Abo-Elyousr et al., 2019; Dönmez et al., 2024) are also of considerable importance today.

This study investigated the suppressive effects of Subtima microbial fertilizer containing *Bacillus subtilis* and RhizoFill microbial fertilizers containing *B. subtilis*, *B. megaterium,* and *Pseudomonas fluorescens* on tomato bacterial canker and wilt diseases.

2. Materials and Methods

Microbial Fertilizers Used in the Study

In the experiment, two different microbial fertilizers (RhizoFill and Subtima) supplied by NG-Biotechnology Ltd. were used (Table 1). Two different doses of each microbial fertilizer were prepared: 250 cc and 500 cc. The prepared solutions were shaken for 24 hours to activate the bacteria.

Table 1. Content and concentrations of microbial fertilizers (Anonymous, 2026b).

Biofertilizers	**Microorganisms**	**Concentrations**
RhizoFill	*Bacillus subtilis*, *Bacillus megaterium*, *Pseudomonas fluorescens*	$1x10^9$ cfu/ml
Subtima	*Bacillus subtilis*	$1x10^9$ cfu/ml

Pathogens Used in the Study

In this study, the isolate of *Clavibacter michiganensis* subsp. *michiganensis* (Cmm-PC-1), isolated from the vascular bundles of tomato plants in the stock culture of the Phytopathology Laboratory of Tokat Gaziosmanpasa University and identified by biochemical tests and molecular analysis (PCR), was used. The bacterial isolate from the stock culture was transferred to Nutrient Agar (NA) medium and incubated at 28 °C for 48 hours to ensure active growth. Bacterial colonies were diluted with saline buffer to a density of 1×10^6 cells mL^{-1}; the suspension density was confirmed by measuring the optical density (OD_{600}) in a spectrophotometer. This suspension was used for inoculation of the plants.

Plant Material

Tomato seedlings of the Alsancak F1 variety were used as plant material. Tomato seeds were germinated in a climate chamber in a growing medium prepared as a soil:peat:perlite (2:1:1) mixture; after reaching a sufficient level of development, they were used in the study.

Application of Microbial Fertilizers, Pathogen Inoculation, and Disease Assessment

In the experiment conducted as a pot experiment in a climate chamber, transplanted seedlings were treated with microbial fertilizer a total of five times at three different periods: before, during, and after pathogen inoculation, at three-day intervals. In each application, 15 ml of solution per plant was applied to the root zone of the seedlings. Pathogen inoculation was carried out 10 days after transplanting the seedlings. The prepared Cmm suspension was applied under the bark of the seedling stem using a sterile syringe, and the plants were placed in a moisture chamber after the application (Figure 1). After inoculation, the plants were monitored at regular intervals, and disease development was recorded.

The treatments used in the experiment are given in Table 2. Negative control group plants received only pure water, while positive control plants received only pathogenic bacteria. The study was set up with 4 replicates, each containing 5 plants, and was repeated twice.

Table 2. Applications used in the experiment

Application Code	Explanation
NC	Negative Control (Pure water application)
PC	Positive Control (*Cmm* application)
P1-250+*Cmm*	RhizoFill-250 cc dose+Cmm
P1-500+*Cmm*	RhizoFill-500 cc dose+*Cmm*
P2-250+*Cmm*	Subtima-250 cc dose+*Cmm*
P2-500+*Cmm*	Subtima-500 cc dose+*Cmm*

The 0–5 scale developed by Francis et al. (2001) was used to assess disease severity. On this scale, a healthy plant was scored as 0, and a dead plant as 5. Scale values were determined based on wilting, leaf blight, and canker ulcer formation in infected plants. Each symptom was assigned a value of 1 if all three symptoms were present, and the disease severity was assessed as 3 if all three symptoms were present. Each plant was evaluated individually, and the total disease score was calculated using the obtained data. Additionally, the length of lesions in the vascular bundles of plants with determined disease severity was measured by cutting the stem lengthwise, and the level of pathogen spread within the plant tissues was determined.



Figure 1. Microbial fertilizer and pathogen application, plants placed in moisture cycling

Statistical Analysis

IBM SPSS Statistics 26 software package was used to evaluate the data obtained at the end of the experiment. A one-way analysis of variance (ANOVA) test was performed to determine whether there were differences between the applications in terms of the examined characteristics, and the Duncan test, a multiple comparison test, was used based on the results of the ANOVA test.

3. Results

In a study conducted to determine the effect of microbial fertilizers on tomato bacterial canker and wilt disease, disease assessment was performed on plants 35 days after pathogen inoculation. Based on assessments of wilting, yellowing, and growth in the plants, the disease severity was determined as 2.25 in PC plants, while the lesion length in the vascular bundles was measured as 13.88 cm. In NC plants treated with only pure water, no symptoms were observed, and no lesions were seen in the stem (Figure 2).

Table 3. Effect of microbial fertilizers on tomato bacterial canker and wilt disease

Application	Scale Value (0-5)	Lesion size (cm)
NC	$0.00\pm0.00^{a*}$	$0.00\pm0.00^{a*}$
PC	2.25 ± 0.96^{d}	13.88 ± 0.94^{f}

P1-250	1.80±0.81^{d}	12.30±0.72^{e}
P1-500	1.60±0.91^{cd}	10.66±0.63^{d}
P2-250	1.00±0.94^{bc}	8.45±2.06^{c}
P2-500	0.87±0.62^{b}	5.84±3.05^{b}

*Means indicated with the same letters in a column are not significantly different.

Compared to PC, the disease severity of RhizoFill at a dose of 250 cc was determined to be 1.80, and the lesion in the vascular bundles was measured as 12.30 cm. With increasing dose (P1-500), a decrease in disease severity and lesion length was observed, with disease severity falling to 1.60 and lesion length to 10.66 cm (Table 3). Subtima applications, however, produced a higher level of suppression compared to RhizoFill. While the scale value was measured as 1.00 and the lesion length as 8.45 cm in the P2-250 application, the lowest disease severity and lesion length were obtained in the P2-500 application. In this application, the scale value decreased to 0.87 and the lesion length to 5.84 cm (Table 3) (Figure 2).

Overall, both microbial fertilizers showed a decrease in disease severity and lesion length with increasing dose; in particular, Subtima at a dose of 500 cc (P2-500) was determined to be the most effective biocontrol application against *C. michiganensis* subsp. *michiganensis.*

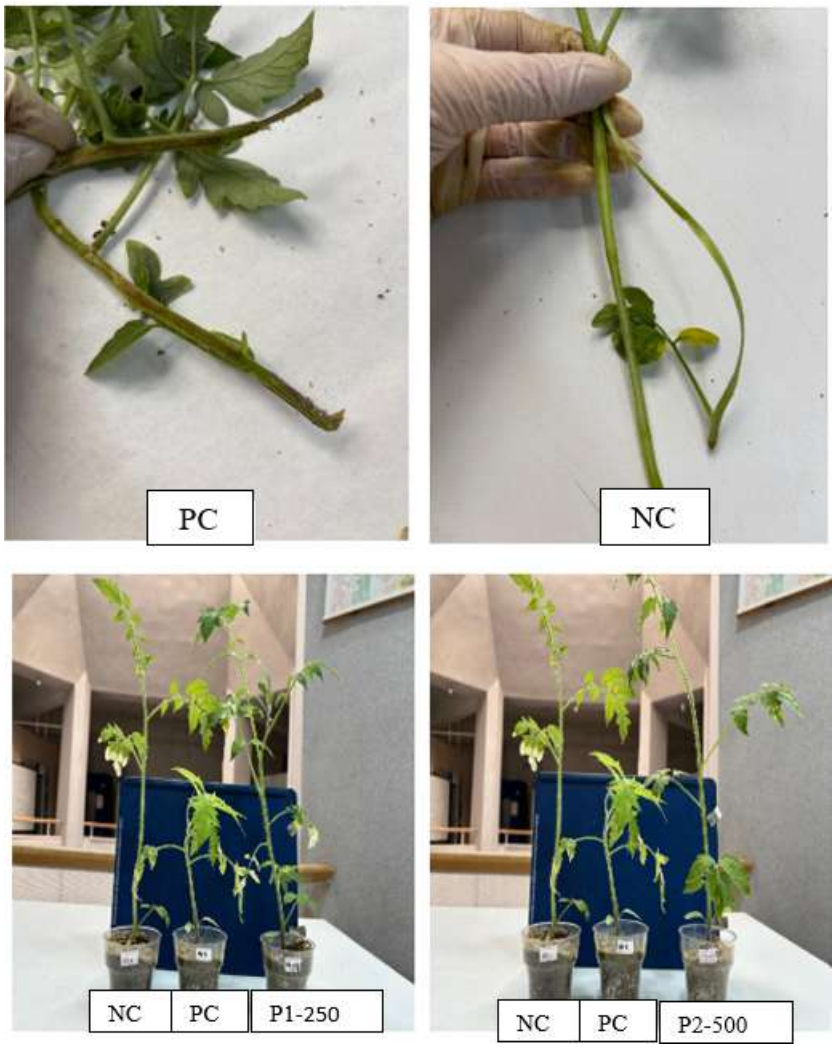


Figure 2. Development of plants treated with NC, PC and microbial fertilizers

Microbial fertilizers, thanks to the beneficial microorganisms they contain, not only support plant nutrition but also provide an important biological defense protecting plants against pathogens. The microorganisms that are the active ingredients of these fertilizers suppress the development of disease agents through multifaceted mechanisms such as antibiotic production, siderophore secretion, competitive colonization with pathogens, competition for nutrients and living space, and the creation of induced systemic resistance (ISR) in the plant (Aslan and Özaktan, 2005; Beneduzi et al., 2012; Meena et al., 2020; Kumar et al., 2022). In this study, it was determined that microbial fertilizer applications containing *Bacillus subtilis*, *B. megaterium*, and *Pseudomonas fluorescens* had a significant biocontrol effect against the pathogen *C. michiganensis* subsp. *michiganensis*. The findings obtained are consistent with some studies in the literature.

In a study conducted by Kılıç (2024), it was reported that in strawberry plants where vermicompost was applied together with RhizoFill and Subtima microbial fertilizers, higher levels of nutrient elements were found in the root and stem tissues, and that biofertilizers supported plant development by increasing nutrient uptake. In another study by Öztürk and Dursun (2023), it was reported that Subtima microbial fertilizer was effective in reducing the negative effects of salt in pepper plants. In a study by Çelik (2023), it was determined that fertilizer applications combined with RhizoFill increased yield parameters in lettuce plants compared to the control. In a study conducted by Karademir et al. (2019), the effects of Coton Plus and Mega Flu commercial biofertilizers on yield and some physiological parameters in cotton were examined. According to the results of the study, yield, stomatal conductivity, and plant temperature (infrared value) were affected by the applications, while no statistically significant difference was observed between the applications in chlorophyll content (SPAD) and greening time (NDVI/Greenseeker). In the study conducted by Parlak et al. (2018), three different doses (3 ml/l, 15 ml/l, 30 ml/l) of two different commercial biofertilizers, Best-doll and Bio-doll, were applied to blue cypress (Cupressus arizonica) and sugar maple (Acer saccharum) seedlings to determine their effect on seedling morphological development under outdoor conditions. The results varied depending on the species and dose. In sugar maple, the 3 ml/l dose of both biofertilizers resulted in an 11-13% increase in seedling height and a 13-16% increase in root collar diameter compared to the control. In contrast, in blue cypress, the control group showed higher height and diameter increases compared to the biofertilizer-treated seedlings.

4. Conclusion

In conclusion, this study demonstrates that RhizoFill and Subtima microbial fertilizers, which support plant growth, have biocontrol potential against the tomato bacterial canker and wilt disease agent *Clavibacter michiganensis* subsp. *michiganensis*. Both microbial fertilizers showed a positive effect in suppressing the disease. Subtima, in particular, significantly reduced disease severity and lesion size. This study is preliminary, and further greenhouse and field studies are needed to further investigate the disease-suppressing properties of microbial fertilizers in these environments.

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EVALUATİON OF THE GOLDEN RATİO AND FEED SYNERGY İN RATİON PREPARATİON: IMPACTS ON PERFORMANCE, ECONOMİCS, SUSTAİNABİLİTY AND CLİMATE CHANGE

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Abstract

This study aimed to investigate the concepts of "Golden Ratio Based Approach" and "Feed Synergy" at both theoretical and experimental levels, with the goal of maximizing environmental sustainability, economic profitability, and animal performance in ruminant production systems. Feed costs constitute 60-70% of total operating expenses. Optimizing this ratio and reducing intestinal methane emissions, one of the biggest negative contributors to global climate change, should be a key focus of modern ration formulation strategies. The study highlights that balancing roughage and concentrate components to maximize microbial protein synthesis not only improves digestibility but also stabilizes rumen homeostasis, thereby preventing metabolic disorders. Furthermore, scientific evidence indicates that the activity of methanogenic archaea can be effectively suppressed through a preventive nutritional strategy involving the incorporation of alternative feed resources, such as agro-industrial by-products, along with functional additives including phytobiotics (tannins, saponins and essential oils). The “Golden Ratio” philosophy extends beyond the quantitative balance of nutrients, offering a holistic resource management framework that is aligned with digestion kinetics and rumen microbiota, while minimizing the environmental footprint per unit of product. Empirical findings demonstrate that strategic ration design creates a mutually beneficial (“win–win”) scenario in livestock production from both ecological and economic perspectives. An approximate 15% reduction in methane emissions achieved through feeding strategies and functional supplementation, combined with improved feed efficiency, enhances the resilience of ruminant production systems to climate change and directly contributes to improved farm profitability.

Keywords: Ration optimization, Golden Ratio, Feed synergy, Methane emissions, Functionalfeed additives, Responsible production and consumption

RASYON HAZIRLAMADA ALTIN ORAN VE YEM SİNERJİSİNİN DEĞERLENDİRİLMESİ: PERFORMANS, EKONOMİ, SÜRDÜRÜLEBİLİRLİK VE İKLİM DEĞİŞİKLİĞİ ÜZERİNE ETKİLERİ

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Özet

Bu çalışma, geviş getiren hayvanların üretim sistemlerinde çevresel sürdürülebilirliği, ekonomik karlılığı ve hayvansal performansı aynı en üst düzeye çıkarmayı amaçlayarak, "Altın Oran Temelli Yaklaşım" ve "Yem Sinerjisi" kavramlarını hem teorik hem de deneysel düzeyde incelemeyi amaçlamıştır. Toplam işletme giderlerinin %60-70'ini yem maliyetleri oluşturmaktadır. Bu oranın optimize edilmesi ve küresel iklim değişikliğinde en büyük olumsuz katkıda bulunanlardan biri olan metan emisyonlarının azaltılması, modern rasyon formülasyon stratejilerinin temel odak noktası olmalıdır. Çalışma, mikrobiyal protein sentezini en üst düzeye çıkarmak için kaba yem ve konsantre yem bileşenlerinin dengelenmesinin sadece sindirilebilirliği iyileştirmekle kalmayıp aynı zamanda rumen homeostazını da stabilize ederek metabolik bozuklukları önlediğini vurgulamaktadır. Ayrıca, bilimsel kanıtlar, metanojenik bakterilerin aktivitesinin, tarımsal-endüstriyel yan ürünler gibi alternatif yem kaynaklarının yanı sıra fitobiyotikler (tanenler, saponinler ve uçucu yağlar) içeren fonksiyonel katkı maddelerinin dahil edilmesini içeren önleyici bir beslenme stratejisi yoluyla etkili bir şekilde bastırılabileceğini göstermektedir. “Altın Oran” felsefesi, besin maddelerinin niceliksel dengesinin ötesine geçerek, sindirim kinetiği ve rumen mikrobiyotasıyla uyumlu, bütünsel bir kaynak yönetimi çerçevesi sunarken, ürün birimi başına çevresel ayak izini en aza indirir. Ampirik bulgular, stratejik rasyon tasarımının, hem ekolojik hem de ekonomik açılardan hayvancılık üretiminde karşılıklı fayda sağlayan (“kazan-kazan”) bir senaryo yarattığını göstermektedir. Yemleme stratejileri ve fonksiyonel takviye ile elde edilen yaklaşık %15'lik metan emisyonu azalması, yem verimliliğinin artmasıyla birleştiğinde, geviş getiren hayvan üretim sistemlerinin iklim değişikliğine karşı direncini artırır ve çiftlik karlılığının doğrudan artmasına katkıda bulunur.

Anahtar Kelimeler: Rasyon optimizasyonu, Altın Oran, Yem sinerjisi, Metan emisyonu, Fonksiyonel yem katkıları, Sorumlu üretim ve tüketim

1. Giriş

Küresel gıda güvenliği stratejik bir konuma sahip olan ruminant hayvancılık, günümüzde çevresel sürdürülebilirlik ve iklim değişikliği gibi makro ölçekli zorluklarla karşı karşıya bırakmaktadır. Bu durumdarasyon optimizasyonu; hem hayvansal performans ve verimliliği maksimize etmek hem de üretimin çevresel ayak izini minimize etmek adına en kritik müdahale alanlarından biri olarak öne çıkmaktadır (Erten ve ark., 2024). Ruminant işletmelerinde yem giderlerinin toplam üretim maliyetlerinin %60-70'ini oluşturduğu gerçeği (Boğa ve çevik, 2012;Ermetin ve Mülayim, 2020), besin madde ihtiyaçlarını fizyolojik sınırlar dahilinde karşılayan optimum rasyonların oluşturulması hayvanın zorunlu bir ekonomik gereklilik haline getirmektedir (Milani ve Milani, 2022). Bu durum, maliyet etkinliğini artırırken hayvan sağlığı ve verimliliğini destekleyen yenilikçi, kapsamlı ve sistemli yaklaşımların geliştirilmesini zorunlu kılmaktadır (Gülsün ve Miç, 2018).

Rasyon formülasyonu, hayvanın yaş, ırk, cinsiyet ve fizyolojik durumu gibi spesifik parametrelerine göre belirlenen günlük gereksinimlerin karşılanmasını hedeflerken; elde edilen denge sadece maliyet avantajı sağlamakla kalmamalı, aynı zamanda yemden yararlanma etkinliğini (YYE) artırarak çevresel sürdürülebilirliğe somut katkılar sunmalıdır (Serbester, 2025; Milani ve Milani, 2022). Bu çerçevede, literatürde "altın oran" ve "yem sinerjisi" olarak nitelendirilen prensipler; rasyonu oluşturan kaba, kesif ve alternatif yem bileşenlerinin birbirini tamamlayarak besin madde sindirilebilirliğini optimize etmesini esas alır. Bu sinerjik etkileşimlerin yönetimi, hayvan sağlığı ve verimlilik hedefleriyle eş zamanlı olarak metan salınımı ve azot atılımı gibi ekolojik çıktıların regülasyonunda anahtar bir rol oynamaktadır.

Lineer programlama gibi geleneksel matematiksel modeller, minimum maliyetli rasyon formülasyonu elde etmek için yaygın olarak kullanılsa da (Boğa ve çevik, 2012;Usigbe ve ark., 2025), modern hayvancılık sistemleri; hayvan refahı, metabolik stabilite ve çevresel etkiler gibi çok boyutlu hedefleri aynı aynı anda değerlendiren optimizasyon yaklaşımlarına ihtiyaç duymaktadır. Bu doğrultuda, besin madde sinerjisini ve "altın oran" dengesini merkeze alan modeller, rasyon bileşenlerinin sindirilebilirliğini artırıp metan salınımını düşürerek hem ekonomik kârlılığı hem de çevresel sürdürülebilirliği eş zamanlı olarak iyileştirmektedir (Akintan ve ark., 2024).

Ruminant beslemede rasyon optimizasyonu, yem bileşenlerinin dengeli kullanımı ile hayvanın fizyolojik gereksinimlerinin uyumlandırılmasını gerektiren kompleks ve çok faktörlü bir analiz alanıdır. Bu alan, kaba-kesif yem dengesi gibi temel rasyonel parametrelerin yanı sıra, alternatif ve fonksiyonel yem kaynaklarının entegrasyonuyla elde edilen sinerjik etkilerin analizini de kapsamaktadır.

Bu çalışmanın temel amacı; ruminant rasyonlarında “altın oran” yaklaşımı ile “yem sinerjisi” prensiplerinin kuramsal temellerini literatür verileri ışığında ortaya koymaktır. Çalışma kapsamında, söz konusu yaklaşımların; hayvansal performans ve yemden yararlanma etkinliği, işletme ölçeğinde ekonomik verimlilik, çevresel sürdürülebilirlik ve spesifik olarak metan emisyonları (mitigasyon), üzerindeki etkileri kapsamlı bir perspektifle değerlendirilmiştir. Ayrıca, farklı yem grupları ve fonksiyonel biyobileşenler arasındaki sinerjik etkileşimlerin rasyon optimizasyonuna olan katkısı analiz edilerek, sürdürülebilir ve maliyet etkin besleme stratejileri için akademik bir çerçeve sunulması hedeflenmiştir.

2. Materyal ve Yöntem

Bu çalışma, ruminant beslemede rasyon optimizasyonu, yem sinerjisi ve metan emisyonunun azaltılmasına yönelik stratejilerin literatür temelli olarak değerlendirilmesi amacıyla yürütülmüş bir derleme çalışmasıdır. Çalışmada Web of Science, Scopus, ScienceDirect ve Google Scholar veri tabanları kullanılarak ilgili literatür taranmıştır. Tarama sürecinde "ruminant nutrition", "methane emission", "feed synergy", "rumen microbiome", "feed additives" ve "alternative feed resources" anahtar kelimeleri kullanılmıştır. Son 16 yıl içinde yayımlanmış hakemli çalışmalar öncelikli olarak değerlendirilmiş, güncel ve yüksek etki faktörlü çalışmaların seçilmesine dikkat edilmiştir.

3. Ruminant Beslemede Rasyon Optimizasyonunun Önemi

Ruminant beslemede rasyon optimizasyonu, Besin Maddesi Kullanım Etkinliğini (BMKE) artırarak hayvansal üretimi maksimize etmeyi ve eş zamanlı olarak azot (N_2) ile fosfor (P) gibi elementlerin çevreye salımını minimize etmeyi hedefleyen multidisipliner bir süreçtir (Haq ve ark., 2024). Bu stratejik dengeleme, sera gazı (SG) emisyonlarının azaltılmasına yönelik küresel projeksiyonlarla uyumlu olup, hayvancılık sektörünün çevresel ayak izini önemli ölçüde iyileştirme potansiyeline sahiptir. Optimizasyon süreçleri, hayvanların genetik potansiyellerini tam olarak göstermelerini sağlayacak şekilde besin maddesi tedarikini hassas bir şekilde ayarlayarak yem verimliliğini artırmakta ve birim ürün başına düşen ekolojik yükü azaltmaktadır (Ojo ve ark., 2024).

Tam yemleme (TMR) uygulamaları gibi yenilikçi yaklaşımlar, yem israfını minimize ederek ve rumen fermentasyon dengesini sağlayarak metan (CH_4) emisyonlarını düşürmektedir (Dey ve ark., 2025). Özellikle yağların ve fonksiyonel yem katkı maddelerinin rasyonlara entegrasyonu, rumen mikro florasını destekleyerek metanojenik aktiviteyi biyokimyasal düzeyde baskılamaktadır (Oliveira ve ark., 2025). Bu stratejiler; genetik seleksiyon, flora manipülasyonu ve hassas yönetim uygulamaları ile entegre bir biçimde değerlendirildiğinde sürdürülebilir hayvancılığa destek sağlamaktadır(Shang ve ark., 2026).

Hassas besleme teknikleri, hayvan refahını optimize etmenin yanı sıra kaynakların korunmasında kritik bir rol oynamaktadır (Şonea ve ark., 2023). Rasyonun bu düzeyde dengelenmesi, mikrobiyal protein sentezini maksimize ederek yemden yararlanma oranını artırmakta, çevresel salınımı ise birim ürün bazında düşürerek yetiştirici karlılığını desteklemektedir (Makkar, 2017). Ayrıca, rasyonlardayüksek sindirilebilirliğe sahip bileşenlerin kullanımı, laktik asidin propiyonik aside dönüşümünü teşvik ederek enerji kayıplarını ve metan salınımını azaltmaktadır (Kılıç ve Boğa, 2021).

Ruminant hayvanların küresel sera gazı salımındaki payı dikkate alındığında, birim alana hayvan başına elde edilecek olan verimin artırılması ve çevresel etkinin azaltılması bir zorunluluk haline gelmiştir (Erten ve ark., 2023). Bu durum, entansif sistemlerde artan girdi maliyetleri ve sıkılaşan çevresel düzenlemeler ışığında stratejik bir öneme sahip olmaktadır (Morshidy, 2025).

Rasyon optimizasyonu, klasik besleme anlayışının ötesine geçerek; verimlilik–kârlılık–sürdürülebilirlik üçgenini dengeleyen kapsamlı bir sistemdir.Literatür, hassas besleme ve fonksiyonel katkıların, yemden yararlanma oranı (YYO) artırırken metanogenezi baskılamada anahtar rol oynadığını doğrulamaktadır (Haq ve ark., 2024; Shang ve ark., 2026). Etkili bir optimizasyon süreci; genetik potansiyel, rumen mikrobiyotası yönetimi ve rasyonel bileşen kompozisyonu ile desteklenmelidir.

Sonuç olarak rasyon optimizasyonu; hayvanların besin madde gereksinmesinin karşılanmasının yanında çevre dostu ve ekonomik hayvansal üretimin temelini oluşturmaktadır.. Gelecekteki çalışmalarında, bu optimizasyon modellerini dijital karar destek sistemleri ile birleştirerek saha şartlarında uygulanabilirliğini artırması, sürdürülebilir hayvancılık için kritik bir gelişim alanı olacaktır.

3.1. Kaba yem ve kesif yem dengesi

Geviş getiren hayvaların besleme stratejilerinde kaba yem ile kesif yem arasındaki en uygun dengenin kurulması; basit bir yem hazırlama işleminin ötesinde, işkembe (rumen) mikroorganizma ekosisteminin iç dengesi ve besin maddesi biyoyararlanımının en üst düzeye çıkarılması açısından yapısal bir zorunluluktur (Hotea ve ark., 2023). Bu dengeleyici oran, rumen pH değerinin fizyolojik sınırlar içinde kararlı kalması ve mikrobiyel tür çeşitliliğinin korunması üzerinde doğrudan düzenleyici bir rol oynayarak, metan üreten mikroorganizmaların etkinliğini kontrol altına almaktadır (Boran ve Serbester, 2022; Ya ve Ak, 2022). Güncel literatür verileri; kaba/kesif yem oranındaki değişimlerin, hayvanın metabolik sağlığı ve performans ölçütlerinin yanı sıra, bağırsak kaynaklı metan üretimini belirleyen rumen fermantasyon devinimini ve modellerini sistemli bir şekilde düzenlediğini kanıtlamaktadır (Roques ve ark., 2023).

Kaba ve kesif yem dengesi üzerine yapılan çalışmaların sentezi, bu oranın rasyonun sadece fiziksel yapısını değil, aynı zamanda rumendeki biyokimyasal sinyalleri de yönettiğini göstermektedir. Rasyon dengesinin bozulmasıyla değişen rumen *pH*'ı, metan üreten bakterilerin yaşam koşullarını etkiler. Bu değişim, bakterilerin hayatta kalma şansını artırarak veya azaltarak metan salınımı üzerinde belirleyici bir rol oynar. Hotea ve ark. (2023) ile Boran ve Serbester (2022) tarafından bildirilen veriler; en uygun rasyon oranının belirlenmesinin hayvansal verimliliği artırırken, metan salınımı gibi çevresel zararları azaltmada en etkili besleme stratejisi olduğunu kanıtlamaktadır. Sonuç olarak; modern geviş getiren besleme modelleri, rasyonel kaba-kesif yem dengesini hem hayvan refahını hem de ekolojik sürdürülebilirliği birlikte ele alan dinamik bir iyileştirme ölçütü olarak kabul etmelidir.

3.2. Karbonhidrat bölümleri ve sinerjik etkileşimler

Rasyon formülasyonunun kuramsal temeli; kaba yemlerin odunsu yapısından gelen yavaş fermente olan karbonhidrat bölümleri ile kesif yemlerin yüksek oranda çözünür nişasta ve şeker içerikleri arasındaki dinamik etkileşime dayanır. Bu uyum (sinerji), yalnızca bir enerji dengesi kurmakla kalmaz; aynı zamanda işkembe kararlılığını artırarak uçucu yağ asidi (UYA) sentezini fizyolojik sınırlar dahilinde en uygun hale getirir. Bu iyileştirme, metabolik enerji kullanım etkinliğini en üst düzeye çıkarırken, metan sentezi (metanogenez) için biyokimyasal açıdan gerekli olan serbest hidrojen (H_2) gibi alt katmanların miktarını ve erişilebilirliğini en aza indirir (Hanušovský ve ark., 2025).

Bu çerçevede, yüksek sindirilebilirliğe sahip yapısal olmayan karbonhidrat kaynaklarının (nişasta vb.) rasyona akılcı bir şekilde dahil edilmesi, işkembe ekosistemindeki metan üretimini baskılama noktasında güçlü bir potansiyele sahiptir (Arslan, 2017). Ancak fermantasyon biçimleri açısından kritik bir ayrım mevcuttur:

Rasyonda kaba yem oranının artması, selülozu parçalayan bakterilerin etkinliğini teşvik ederek asetat (sirke asidi) üretimini artırır. Bu süreçte açığa çıkan hidrojen, metanojenik bakteriler tarafından metan sentezi için hammadde olarak kullanılır.

Rasyondaki kesif yem oranının artması, nişastayı parçalayan bakterileri canlandırarak propiyonat üretimini hızlandırır. Propiyonat oluşumu sırasında ortamdaki hidrojen kullanıldığı için, metan üreten bakterilerin ihtiyaç duyduğu hammadde azalır; böylece metan üretimi biyokimyasal olarak engellenmiş olur. Ancak rasyondaki kesif yem oranının kontrolsüz ve ani bir şekilde artırılması, işkembe ekosisteminde dengeleri bozarak beklenmedik ve riskli sonuçlara yol açabilmektedir. Kontrolsüz karbonhidrat yüklemesi; laboratuvar ortamındaki (*in vitro*) gaz üretim değerlerini ve toplam organik madde sindirilebilirliğini etkilemekle kalmaz; aynı zamanda işkembe asitliğindeki dalgalanmalara bağlı olarak metan salınımında beklenmedik artışlara veya ciddi metabolik bozukluklara (asidoz vb.) neden olabilir (Erten ve ark., 2024).

Sonuç olarak; karbonhidrat bölümleri arasındaki bu hassas denge, hayvansal verimliliğin artırılması ile çevresel etkilerin azaltılması hedefleri arasında bir köprü kurarak, rasyon formülasyonunun en temel yapı taşını oluşturmaktadır.

3.3. İşkembe (Rumen) fermantasyonunun yönlendirilmesi ve mikrobiyel güvenlik

Aşırı kesif yem kullanımı veya karbonhidrat bileşimindeki ani müdahaleler, rumen *pH*'sını kritik eşiklerin altına düşürerek yarı akut işkembe asitliğine yol açabilmektedir. Bu durum sadece metan üreten mikroorganizmaları değil, selülozu parçalayan (selülolitik) bakteriler gibi faydalı mikrobiyel toplulukları da olumsuz etkilemektedir (Li ve ark., 2021; Sun ve ark., 2022). Bu nedenle, yem karmasında optimum dengenin kurulması; metan salınımının kontrol altına alınması ile rumen sağlığı ve hayvansal üretimin sürdürülebilirliği arasındaki dengenin korunması açısından stratejik bir öneme sahiptir (Hristov, 2024; Ribeiro ve ark., 2015).

Geviş getiren hayvanların beslenmesinde, yemlerin işkembede kalış süresini kısaltan ve sindirim akışını hızlandıran yaklaşımlar, metan oluşumu için gereken zamanı daraltarak çevresel etkiyi doğrudan azaltabilmektedir (Arslan, 2017). Elde edilen veriler, sindirilebilirliğin artırılmasının ve metabolik hidrojen kullanımının metan üreten bakteriler yerine propiyonat üreten bakterilere yönlendirilmesinin merkezi önemini ortaya koymaktadır (Bogolyubova, 2023; Smith ve ark., 2022). Nitekim, yüksek kesif yem içeren rasyonların, birim süt veya et üretimi başına metan salınımını yaklaşık %15 oranında azaltabildiği saptanmıştır; ancak bu kazanım, dikkatle yönetilen bir kaba/kesif yem dengesine bağlıdır (Grossi ve ark., 2018).

Rasyona eklenen yağ asitleri gibi katkılar metan azaltımına katkı sağlarken, yüksek tahıl içerikli besleme modellerinin risk faktörleri (asidoz ve beklenmedik metan artışı potansiyeli) göz ardı edilmemelidir (Kaplan, 2025).

Sonuç olarak, kaba yem–kesif yem dengesi, geviş getiren hayvan beslemede sadece matematiksel bir oran değil, işkembe ekosisteminin tüm işlevlerini düzenleyen anahtar bir mekanizmadır. literatür, bu dengenin doğru kurulmasıyla sindirim verimliliğinin artırılabildiğini ve metan salınımının kontrol altına alınabildiğini açıkça göstermektedir. Sadece kesif yem artırımına dayalı tek yönlü yaklaşımlar kısa vadeli kazanımlar sağlasa da, uzun vadeli sürdürülebilirlik için yem kalitesi, sindirilebilirlik ve sinerjik etkileşimler rasyon bütünlüğü içinde planlanmalıdır.

3.4. Alternatif ve işlevsel yemlerin yükselen önemi

Geviş getiren hayvanların besleme yöntemlerinde, geleneksel yem kaynaklarına olan bağımlılığın azaltılması ve çevresel sürdürülebilirliğin artırılması amacıyla alternatif yem

kaynakları ile işlevsel (fonksiyonel) katkı maddelerinin kullanımı merkezi bir önem kazanmıştır. Bu stratejik yaklaşım, rasyonun besin yoğunluğunu zenginleştirerek hayvansal performansı en üst düzeye çıkarmanın yanı sıra, metan salınımı gibi ekolojik yüklerin azaltılmasında belirleyici bir rol oynamaktadır (Malyugina ve ark., 2025). Bu doğrultuda, tarımsal sanayi yan ürünleri ve bitkisel ikincil (sekonder) metabolitler, sindirim devinimini iyileştirme ve bağırsak kaynaklı metan salınımını baskılama potansiyelleriyle öne çıkmaktadır (Boran ve Serbester, 2022).

Bitkisel özütler (fitobiyotikler) ve biyoaktif bileşikler, işkembe (rumen) ekosistemindeki metan üreten mikroorganizmaların etkinliğini hedef alarak metan üretim yollarını biyokimyasal düzeyde engelleyebilmektedir (Hassan ve ark., 2020; Palangı ve Lackner, 2022). Bu süreçte metanojenlerin alt katmanlara erişiminin kısıtlanması veya metabolik yolların baskılanması temel mekanizmalardır (Malyugina ve ark., 2025; Muruz ve Sertkaya, 2022). Özellikle uçucu yağlar, tanenler ve saponinler; hidrojen akışını metan oluşumundan uzaklaştırarak propiyonat üretimine yönlendirmekte, böylece enerji kaybını azaltırken çevresel karbon ayak izinide düşürmektedir (Arslan, 2017; González-Ronquillo ve Toro-Mújica, 2023). Bu tür bileşenlerin rasyona dahil edilmesi, yemden yararlanma oranını (YYO) artırarak üretimin sürdürülebilirliğine katkı sağlamaktadır (Shinkai ve ark., 2023).

İnsan tüketimine uygun olmayan alternatif kaynakların değerlendirilmesi, "yem–gıda rekabetini" en aza indirerek maliyet etkinliğini artırmaktadır (Pámanes-Carrasco ve ark., 2020). Ancak, bitkisel özütlerin bağırsak sağlığı ve metan salınımı üzerindeki olumlu etkilerine rağmen, uygulama dozu ile rasyon bileşimi arasındaki ilişkinin dikkatle analiz edilmesi gerekmektedir (Boğa ve ark., 2021; Patra, 2022). Bu doğal bileşikler, özellikle antibiyotik kısıtlamalarının olduğu sistemlerde verim artırıcı ilaçlara alternatif olarak işlev görmektedir (Oruç ve Avcı, 2018). Buna karşın, söz konusu bileşiklerin etkinliği; kimyasal yapılarına, dozajlarına ve hayvan türüne göre farklılık gösterebilmektedir (Denek ve ark., 2014).

Literatür bulguları, işlevsel yemlerin etkisinin standart olmadığını; doz-yanıt ilişkisi ve rasyonun diğer bileşenleriyle olan etkileşimine göre şekillendiğini doğrulamaktadır. Bu durum, "tekil bileşen" odaklı yaklaşım yerine, uyumlu etkileşimleri (sinerji) temel alan bir formülasyon yapısını zorunlu kılmaktadır. Alternatif kaynakların kullanımı, gıda güvenliğini desteklerken metan emisyonlarını biyokimyasal yollarla engelleyerek hayvancılığı küresel iklim hedefleriyle uyumlu hale getirmektedir.

Özetle, işlevsel yem katkı maddeleri; kârlılık ve ekolojik dengeyi birleştiren güçlü birer araçtır. Bu katkıların işkembe ekosistemi üzerindeki kalıcı etkilerinin, yeni nesil dijital takip sistemleri ve hassas besleme yaklaşımlarıyla birlikte incelenmesi, hayvancılıkta sürdürülebilir bir teknolojik dönüşümün kapısını aralayacaktır.

4. Ruminant Beslemede "Yem Sinerjisi" Kavramı

Rominant hayvanların besleme stratejilerinde "yem sinerjisi"; farklı yem bileşenlerinin bir araya gelerek, tekil etkilerinin toplamından daha yüksek bir biyolojik yanıt oluşturması süreci olarak tanımlanmaktadır. Bu kavram, rasyon formülasyonunda durağan besin maddesi hesaplamalarından, dinamik etkileşim yönetimine geçişi temsil eder. Sinerjik mekanizmalar; yemlerin sindirilebilirliğini en üst düzeye çıkarmak, bağırsak emilimini iyileştirmek ve işkembe (rumen) mikroflorasını metan azaltımı yönünde düzenlemek suretiyle hayvan sağlığı ile üretim verimliliğini eş zamanlı olarak desteklemektedir (Hassan ve ark., 2020).

Rasyonda işlevsel (fonksiyonel) katkı maddelerinin, özellikle bitkisel özütler (fitobiyotikler) ve probiyotiklerin birlikte kullanımı; besin kullanım etkinliğini artırırken bağırsak kaynaklı (enterik) metan salınımını baskılayan bir biyolojik hızlandırıcı görevi görmektedir (Ahmed ve ark., 2024). Bu doğrultuda, tanen içeren bitki ikincil (sekonder) metabolitlerinin rasyona dahil edilmesi, rumen fermantasyon devinimini iyileştirmekte ve yemden yararlanma oranları üzerinde olumlu bir ilişki sergilemektedir (Boğa ve ark., 2021; Hidayah, 2016; Khejornsart ve ark., 2024).

Doğal bileşiklerin stratejik kombinasyonları, rasyonun etkisini besleme fizyolojisinin ötesine taşıyarak bağışıklık üzerinde de belirleyici rol oynamaktadır. Uçucu yağlar ile organik asitlerin sinerjik birlikteliği, rumen ölçütlerini en uygun hale getirerek hem metan oluşumunu engellemekte hem de metabolik verimliliği artırmaktadır (Nhara ve Baloyi, 2025). Bu durum, hayvan refahını yükselterek antibiyotik kullanımına duyulan ihtiyacı en aza indirmekte ve "Tek Sağlık" yaklaşımı çerçevesinde sürdürülebilir üretim modellerine veri sunmaktadır (Amalyadi, 2025; Nastoh ve ark., 2024).

Yem sinerjisi yaklaşımı, tekil bileşen analizine dayalı geleneksel yöntemlerin yerini alan; kapsamlı, sistemli ve tamamlayıcı bir öğretidir. Literatür verileri, uygun yem kombinasyonlarının oluşturulmasının yalnızca bir rasyon dengeleme işlemi değil, aynı zamanda karmaşık bir rumen ekosistemi mühendisliği olduğunu göstermektedir. Rasyon hazırlarken sadece ham besin maddesi düzeylerine odaklanmak, bileşenler arasındaki biyokimyasal etkileşimlerin potansiyelini göz ardı etmek anlamına gelir. Sinerji yaklaşımı, bu gizli potansiyeli açığa çıkararak metabolik kayıpları en aza indirir.

Sonuç olarak; yem sinerjisi; verimlilik, hayvan sağlığı ve ekolojik koruma ölçütlerini aynı düzlemde iyileştiren stratejik bir araçtır. Gelecekteki araştırmaların, bu sinerjik etkileşimlerin moleküler düzeydeki mekanizmalarını aydınlatmaya ve hassas hayvancılık teknolojileriyle bu etkileşimleri saha düzeyinde kontrol etmeye odaklanması gerekmektedir.

4.1. Altın oran yaklaşımının teorik temeli

Geviş getiren hayvanların rasyon formülasyonunda modern bir model değişimini temsil eden "Altın Oran" yaklaşımı; kaba ve kesif yem bileşenlerinin miktar bazlı birleşiminin ötesine geçerek; biyoyararlanım, sindirim devinimi (kinetiği) ve işkembe (rumen) mikroorganizma ekosistemi arasındaki dinamik etkileşimi esas alan kapsamlı bir model sunmaktadır. Bu yaklaşım, hayvanın fizyolojik dengesi ile üretim hedeflerini, çevresel sürdürülebilirlik ölçütleriyle eşgüdümlü hale getiren çok boyutlu bir iyileştirme sürecidir. Rasyon bileşenleri arasındaki uyumun (sinerjinin) sistemli yönetimi, metabolik verimliliğin en üst düzeye çıkarılmasına; paralel olarak metan salınımı ve azot atılımı gibi çevresel olumsuzlukların en aza indirilmesine olanak tanımaktadır (Nasir ve ark., 2025).

Altın oran stratejisinin temel dayanağı, rumen fermantasyon ürünlerinin yönlendirilmesi aracılığıyla enerji kullanım etkinliğini en üst düzeye çıkarmaktır. Bu süreçte, uçucu yağ asitleri (UYA) profilinin en uygun hale getirilmesi ve mikrobiyel protein sentezinin uyarılması, stratejinin belirleyici bileşenlerini oluşturur. Yazınla uyumlu olarak, optimize edilmiş rasyonların yem alımını teşvik ettiği (Bąkowski ve Kiczorowska, 2020) ve yemden yararlanma oranlarında iyileşme sağladığı saptanmıştır (Hotea ve ark., 2023). Bu iyileşme, işletme ölçeğinde ekonomik sürdürülebilirliği güçlendirirken, makro ölçekte çevresel düzenlemelere uyumu kolaylaştırmaktadır.

Kaba yemlerin lif içeriği ile kesif yemlerin enerji yoğunluğu arasında kurulan en uygun denge, rumen sağlığının korunması ve sindirim sisteminin etkin çalışması açısından kritik bir eşiktir (Nhara ve Baloyi, 2025). Bu dengeleyici mekanizma, geviş getirenlerin günlük besin ihtiyaçlarının hassas bir şekilde karşılanmasını sağlayarak; aşırı veya yetersiz beslemeye bağlı verim kayıplarını en aza indirir (Milani ve Milani, 2022). Mikroorganizma popülasyonunun dengeli düzenlenmesi, sadece hayvansal performansı artırmakla kalmayıp, metan emisyonlarının azaltılması ve azot kullanım etkinliğinin artırılması gibi küresel çevresel hedeflerle uyumlu bir üretim modeli oluşturulmasına katkı sağlar.

Rasyon optimizasyonunda "Altın Oran" yaklaşımı; hayvan gereksinimlerini en düşük maliyetle karşılamayı hedeflerken (Gülsün ve Miç, 2018), aynı zamanda sürdürülebilirlik ve çevresel etkilerin azaltılması ilkelerini bütünsel bir şekilde dikkate alan ileri düzey bir besleme stratejisidir (Agabriel, 2007). Elde edilen veriler, bu yaklaşımın klasik rasyon dengeleme anlayışının ötesine geçtiğini ve verimlilik–çevre–ekonomi üçgenini eş zamanlı olarak iyileştiren bir model sunduğunu göstermektedir. Bu modelin başarısı; sadece doğru oranların matematiksel olarak hesaplanmasına değil, yem bileşenlerinin kalite özellikleri ile rumen mikrobiyel yanıtlarının dinamik yönetimine bağlıdır.

Özetle, hassas besleme teknolojilerinin dijital karar destek mekanizmalarıyla birleşmesi, hayvancılıkta yeni bir dönemi temsil etmektedir. Bu sinerji, rasyondaki teorik ideal dengenin (Altın Oran), değişken saha koşullarına dinamik bir şekilde uyarlanmasını sağlayarak verimlilik ve sürdürülebilirliği en üst seviyeye taşıyabilecektir.

4.2. Sinerjik beslemenin sürdürülebilirlik ve iklim değişikliği ile ilişkisi

Ruminant hayvancılığı, küresel gıda güvenliğinin sağlanmasında hayati bir rol oynamasına rağmen, metan salınımı başta olmak üzere çevresel etkileri nedeniyle iklim değişikliğiyle mücadele stratejilerinin temel odak noktalarından biridir (Inan ve ark., 2025). Bu doğrultuda, yem rasyonlarında yapılan düzenlemeler ve yem sinerjisinden faydalanılması; hem hayvan başına düşen metan salınım yoğunluğunu hem de toplam emisyon miktarını azaltarak iklim hedeflerine ulaşmada kritik bir araçtır (Arndt ve ark., 2022). Rasyon optimizasyonuna dayalı hassas besleme stratejilerinin uygulanması, yalnızca üretim verimliliğini artırmakla kalmayıp, aynı zamanda çevresel ayak izini küçülterek sürdürülebilir hayvancılık sistemlerinin gelişimine katkı sağlamaktadır (Ojo ve ark., 2024).

Özellikle temel (esansiyel) amino asit dengelerinin en uygun hale getirilmesi, azot kullanım etkinliğini artırarak çevresel yükü azaltma potansiyeli sunmaktadır (Șonea ve ark., 2024). Rasyonlarda protein düzeylerinin hassas bir şekilde ayarlanması, amonyak uçuculuğunu ve nitrat yıkanmasını azaltarak hem su hem de hava kalitesinin korunmasına yardımcı olur (Xiao ve Meng, 2024). Ayrıca, yüksek lif içeriğine sahip yemlerin rasyona dahil edilmesi, işkembe (rumen) mikrobiyel etkinliğini destekleyerek azot kullanımını iyileştirebilir ve amonyak salınımını azaltabilir (Haq ve ark., 2024). Bu durum, hayvancılık sistemlerinin yalnızca gıda üretimine değil, aynı zamanda çevresel sürdürülebilirliğe de hizmet eden bir yapıya dönüşmesini sağlamaktadır (Guyader ve ark., 2016).

Yerel kaynaklı ve tarımsal sanayi (agro-endüstriyel) atık bazlı yemlerin rasyonlara dahil edilmesi, döngüsel ekonomi yaklaşımını destekleyerek hem üretim maliyetlerini düşürmekte hem de çevresel etkiyi en aza indirmektedir (Chisoro ve ark., 2023). Bu çalışma, ruminant beslemede rasyon optimizasyonunun yalnızca verimlilik odaklı değil, aynı zamanda çevresel sürdürülebilirlik ekseninde değerlendirilmesi gerektiğini ortaya koymaktadır.

Literatür, özellikle hassas besleme ve yem sinerjisinin birlikte ele alınmasının hem azot hem de metan kaynaklı çevresel yükleri azaltmada etkili olduğunu göstermektedir. Ancak bu stratejilerin saha uygulamalarındaki başarısı; bölgesel yem kaynaklarına, ekonomik koşullara ve üretim sistemlerine bağlı olarak değişkenlik göstermektedir. Bu nedenle, rasyon optimizasyonu yaklaşımının kapsamlı bir bakış açısıyla ele alınması ve ekonomik-çevresel dengeyi gözeten modellerle desteklenmesi gerekmektedir.

5. Rasyonel Etkileşimler ve Uygulama Sonuçları

5.1. Kaba ve kesif yemler arasındaki sinerjik etkileşimler

İşkembe (rumen) fermantasyonunun biyolojik etkinliği ve mikrobiyel protein sentezi; yalnızca rasyondaki karbonhidrat ve azotun miktarına değil, aynı zamanda bu bileşenlerin rumendeki parçalanma hızları arasındaki fermantatif eş güdüme bağlıdır (Konyalı ve ark., 2004). Bu eş güdüm, akılcı bir şekilde iyileştirilmiş kaba ve kesif yem oranları aracılığıyla besin maddesi biyoyararlanımını artırmakta; zooteknik performans ile ekonomik karlılığı eş zamanlı olarak en üst düzeye çıkarmaktadır (Konyalı ve ark., 2004).

Karbonhidrat ve azot kaynaklarının rumende eş zamanlı olarak parçalanması, mikrobiyel biyokütle üretiminin en uygun hale getirilmesi açısından kritik bir önkoşuldur. Bu doğrultuda, özellikle maya gibi biyoteknolojik yem katkıları, rumen mikro-ortamını kararlı hale getirerek mikrobiyel etkinliği teşvik etmekte ve sindirim süreçlerinin fizyolojik verimliliğini artırmaktadır (Kipkorir ve ark., 2024; Dey ve ark., 2025).

Kaba ve kesif yemler arasındaki en uygun denge, rumen *pH* değerini fizyolojik sınırlarda (6.2-6.8) tutarak selülozu parçalayan bakterilerin etkinliğini ve uçucu yağ asidi (UYA) üretimini artırırken; yarı akut rumen asitliği gibi metabolik bozuklukların önlenmesinde tampon görevi görmektedir (Kipkorir ve ark., 2024).

Rasyonel azot yönetimi, bu karmaşık sistemin en hassas bileşenlerinden biridir. Özellikle "bypass" (rumende parçalanmayan) protein kaynaklarının stratejik kullanımı, proteinin ruminal yıkım sonucu aşırı parçalanmasını engelleyerek hem mikrobiyel protein sentezini desteklemekte hem de amonyak-azot (NH_3-N_2) atılımını azaltarak çevresel azot yükünü en aza indirmektedir (Polat ve ark., 2007). Karbonhidrat ve azot eş güdümü; amonyak birikimi ve enerji kayıplarını (metan ve ısı) düşürürken, kuru madde (KM) ve yapısal karbonhidratların sindirilme oranını artırmaktadır (Silva ve ark., 2013).

Bu dengeli yapı, biyolojik verimliliğin yanı sıra ekonomik dayanıklılık açısından da temel bir ölçüttür. Güncel üretim modellerinde yemden yararlanma oranı (YYO), hammadde birim maliyetinden ziyade, işletme karlılığını doğrudan etkileyen temel bir finansal gösterge ve verimlilik kriteri olarak kabul edilmektedir. (Çimen ve ark., 2005). Bu noktada, Metabolize Edilebilir Protein (MEP) sistemi gibi gelişmiş protein değerlendirme yaklaşımları, geviş getirenlerin fizyolojik ihtiyaçlarının hassasiyetle karşılanmasına olanak tanımaktadır (Öğüt ve Çetinkaya, 2020).

Rumen parçalanabilir protein (RDP) ve rumen parçalanmayan protein (RUP) bölümleri arasındaki denge; toplam uçucu yağ asidi üretimi, mikrobiyel yenilenme ve genel sindirim devinimi (kinetiği) üzerinde belirleyici bir rol oynamaktadır (Zain ve ark., 2024). Enerji ve protein düzeylerinin eş güdümlü bir biçimde artırılması, amonyak yoğunluğunu ve UYA

üretimini en uygun hale getirerek toplam metabolik verimliliği iyileştirmektedir (Putri ve ark., 2021).

Enerji (karbonhidrat) ve azotun işkembede eş zamanlı olarak kullanıma sunulması, mikrobiyel aktivitenin en üst seviyeye çıkmasını sağlar ve bu durum hayvansal üretimin temel verimlilik motoru olarak kabul edilir. Bu denge, mikrobiyel protein sentezini optimize etmenin yanı sıra, çevresel azot kayıplarını ve birim ürün maliyetini azaltan çok yönlü bir etki yaratmaktadır. Gelecekte, rasyon formülasyonlarında statik besin değerleri yerine parçalanma devinimine dayalı dinamik modellerin ve MEP gibi gelişmiş sistemlerin kullanımı, hayvancılık sektöründe hem ekonomik karlılığı hem de ekolojik sürdürülebilirliği güvence altına alacaktır.

5.2. Alternatif yemlerin rasyona entegrasyonu ve etkileri

Geleneksel olmayan yem kaynaklarının kullanımı, yalnızca girdi maliyetlerini düşürmekle kalmayıp, tarımsal yan ürünlerin besin zincirine yeniden kazandırılmasını sağlayarak biyo-ekonomik sistemlerin etkinliğini artırmaktadır. Alternatif protein kaynakları olan pamuk tohumu ve kanola küspesi, sadece ekonomik olmakla kalmayıp, işkembe fermantasyonu ve sindirilebilirlik açısından soya küspesine yakın verimlilik sunarak sürdürülebilir bir besleme stratejisi sağlamaktadır (Mi ve ark., 2022). Bu hammaddelerin biyoteknolojik fermantasyon süreçlerinden geçirilmesi, ham protein biyoyararlanımını artırmakta ve besleme karşıtı (antinutrisyonel) faktörlerin elenmesi açısından stratejik avantajlar sağlamaktadır (Rehemujiang ve ark., 2023).

Alternatif yemlerin akılcı bir şekilde rasyona eklemlenmesi, enerji ve protein kaynakları arasındaki fermantasyon uyumunun hassasiyetle yönetilmesine bağlıdır. Bu uyum, işkembe mikroorganizmaları için en uygun besiyerini oluşturarak mikrobiyel protein sentezini en üst düzeye çıkarmakta ve azot kullanım etkinliğini (AKE) artırmaktadır (Silva ve ark., 2013). Söz konusu iyileştirme, hayvansal üretim kaynaklı çevresel azot salınımlarının azaltılmasında da kilit rol oynamaktadır (Seo ve ark., 2013; Shen ve ark., 2015). Metabolize edilebilir protein gereksinimlerinin hassas ölçümü ve aşırı azot yüklemesinin engellenmesi, hem işletme kârlılığı hem de ekolojik ayak izinin küçültülmesi açısından elzemdir (Erten ve ark., 2023; Öğüt ve Çetinkaya, 2020).

Bu doğrultuda, rasyonda işkembe parçalanabilir protein (RDP) ile parçalanmayan protein (RUP) bölümleri arasındaki dengenin korunması metabolik bir zorunluluktur. Mikroflora için yeterli düzeyde parçalanabilir protein sağlanırken, hayvanın "işkembeden kaçan" (bypass/RUP) protein ihtiyacının karşılanması; zooteknik performans ve toplam sindirilebilirlik üzerinde belirleyici bir ölçüttür (Lu ve ark., 2019; Putri ve ark., 2021). Bu dinamik denge, yüksek proteinli diyetlerde dahi amonyak-azot (NH_3-N_2) yoğunluğunu fizyolojik sınırlarda tutarak azotun metabolik verimliliğini artırmaktadır (Muruz ve ark., 2017; Yunilas ve ark., 2024).

Alternatif protein kaynaklarının kullanımı, fermantasyon ölçütleri üzerinde de olumlu düzenlemeler oluşturabilmektedir. Örneğin; hardal küspesi takviyesinin kuru madde (KM) ve organik madde (OM) sindirilebilirliğini teşvik edebildiği; fermantasyon teknolojilerinin ise hammaddelerdeki gossypol ve glukosinolat gibi toksik bileşenleri en aza indirerek besin değerini yükselttiği saptanmıştır (Ünay ve ark., 2019; Yusuf ve ark., 2021). Özellikle yüksek protein içeriğiyle (%34–40) dikkat çeken pamuk tohumu küspesi ve biyoyakıt endüstrisinin yan ürünü olan karinata unu gibi kaynaklar; enerji yoğunluğu ve düşük maliyet avantajlarıyla rasyon hazırlamada stratejik seçenekler olarak öne çıkmaktadır (Rehemujiang ve ark., 2023; Ismael ve ark., 2023).

Ruminant hayvan beslemede alternatif yem kaynaklarının kullanımı, sadece maliyet odaklı bir yer değiştirme yöntemi değil, sürdürülebilir hayvancılığın yapısal bir bileşenidir. Ancak bu kaynakların potansiyelinden tam manasıyla yararlanabilmek için; sindirilme oranları, besleme karşıtı içerikler ve işkembe fermantasyon dinamikleri disiplinler arası bir yaklaşımla analiz edilmelidir. Gelecek öngörülerinde, fermantasyon teknolojileri ve protein bölümlerinin uyumlu yönetimi, bu alternatiflerin biyo-ekonomik değerini en üst düzeye çıkararak üretim verimliliğini ve çevresel uyumu artıracaktır.

5.3. Fonksiyonel yemlerin metan azaltımı üzerindeki rolü

Ruminant beslemede enterik metan (CH_4) salınımlarını baskılamaya yönelik geliştirilen biyoteknolojik stratejiler arasında; fitobiyotikler, esansiyel yağlar, tanenler ve saponinler gibi işlevsel (fonksiyonel) yem katkı maddeleri merkezi bir rol oynamaktadır. Bu biyoaktif bileşenler, işkembe (rumen) mikroorganizma topluluğunu seçici bir yaklaşımla düzenleyerek metan üreten aktiviteyi engellemekte veya metabolik hidrojeni alternatif kullanım yollarına (örneğin propiyonat sentezi) aktarmaktadır (Mrutu ve ark., 2025; Oliveira ve ark., 2025). Özellikle tanenlerin, işkembe protozoa popülasyonunu azaltarak, bu canlılarla ortak yaşam içindeki metanojenik bakterilerin etkinliğini düşürdüğü bildirilmektedir (İpçak ve ark., 2017).

Tanenlerin etki mekanizması, diyet proteinleri ile kararlı kompleksler oluşturarak işkembe protein yıkımlanmasını sınırlaması ve "işkembede parçalanmayan protein" (bypass protein) oranını artırmasının yanı sıra, metan üreten mikroorganizmaların hammadde erişimini fiziksel ve kimyasal olarak kısıtlaması esasına dayanmaktadır. Benzer şekilde saponinler, protozoaların hücre zarlarındaki sterollerle etkileşime girerek bu canlıların popülasyonunu baskılamakta, metan üretimini engellemekte ve işkembe fermantasyon biçimini enerji verimliliğini artıracak şekilde düzenlemektedir (Berça ve ark., 2023). Genel bir bakış açısıyla bitkisel ikincil (sekonder) bileşenler, işkembe ekosistemini yeniden yapılandırarak enerji kaybına yol açan metan salınımları azaltmakta ve toplam yem enerjisi biyoyararlanımını yükseltmektedir (Cengiz ve Kamalak, 2020).

Mikrobiyal kökenli stratejiler kapsamında; probiyotik, prebiyotik ve sinbiyotik kombinasyonları da işkembe mikroorganizma topluluğunun dengelenmesi aracılığıyla metan salınımını düzenleme potansiyeline sahiptir (Michalak ve ark., 2021; Sun ve ark., 2021). Özellikle fermente yem uygulamaları ve probiyotik takviyeler, işkembe mikroflorasını daha dirençli ve dengeli bir yapıya kavuşturarak metan üreten bakterilerin çoğalmasını baskılamakta ve besin maddesi kullanım etkinliğini artırmaktadır (Elbaz ve Khidr, 2024). Ayrıca, kondanse tanenler gibi ikincil bileşenlerin kullanımı, rumen içi redoks (indirgenme-yükseltgenme) potansiyelini değiştirerek metanojenik bakterilerin enzim sistemlerini dolaylı yoldan baskılamakta ve metan salınım yoğunluğunu düşürmektedir (Gerardo ve ark., 2019; Kelln ve ark., 2020; Holik ve ark., 2025).

İşlevsel yem bileşenleri, ruminant üretim sistemlerinde metan salınımlarının kontrolü için sürdürülebilir ve yüksek potansiyelli bir "biyo-araç seti" sunmaktadır. Ancak bu bileşenlerin etkinliği, tekil kullanımlarından ziyade işkembe mikrobiyal ekosistemi üzerindeki ortak etkileşimli (sinerjik), kapsamlı ve sistemli etkilerinin yönetimine bağlıdır. Gelecekteki uygulamaların; doz-yanıt ilişkisi netleştirilmiş karma yöntemleri ve mikroorganizma odaklı hassas besleme modelleri ile desteklenmesi, hem çevresel sürdürülebilirlik hem de hayvansal üretim ekonomisi açısından büyük ölçekli iyileşmeler sağlayacaktır.

6. Altın Oran Yaklaşımının Rasyon Dengesi ve Sindirilebilirlik Üzerine Etkisi

Ruminant beslemede en uygun rasyon dengesi, besin maddesi kullanım etkinliğini en üst düzeye çıkarırken enterik metan salınımlarını en aza indiren temel belirleyici faktördür. Bu doğrultuda "Altın Oran" yaklaşımı; kaba ve kesif yem oranları ile protein, enerji ve mikro besin öğelerinin hassas dengelenmesini hedefleyen akılcı bir stratejiyi temsil etmektedir. Bu yaklaşım, yem bileşenleri arasındaki ortak etkileşimli (sinerjik) etkileri temel alarak, hayvan performansını ve çevresel sürdürülebilirliği eş zamanlı olarak iyileştirmeyi amaçlamaktadır.

Bu stratejik çerçevede, tanen içeriği yüksek yem kaynaklarının kullanımı metan oluşumunun baskılanmasında kritik bir rol oynamaktadır. Tanenler, işkembe (rumen) mikrobiyal ekosistemini ve fermantasyon biçimlerini düzenleyerek propiyonat üretimini teşvik etmekte; böylece metabolik hidrojeni metan oluşum yolları yerine alternatif yapım (anabolik) yollarına yönlendirmektedir (Kılıç ve Boğa, 2021; Göncü ve Kaya, 2024; Hidayah, 2016). Ayrıca, bitkisel ikincil (sekonder) bileşenlerin, işkembe mikroorganizma topluluğu (mikrobiyom) yapısını hedefleyerek metan sentezinden sorumlu metanojenik bakterilerin çeşitliliğini ve işlevsel aktivitesini doğrudan engellediği bildirilmektedir (Kú-Vera ve ark., 2020).

Bu biyokimyasal etki mekanizmasına ek olarak; probiyotik, prebiyotik ve postbiyotik karakterdeki mikrobiyal yem katkıları, işkembe fermantasyonunu dengeleyerek metan oluşumunu dolaylı yollarla düzenlemektedir (Thacharodi ve ark., 2024; Xie ve ark., 2025). Probiyotik uygulamalar, işkembe içi indirgenme-yükseltgenme potansiyelini ve *pH* dengesini en uygun hale getirerek faydalı mikroflora gelişimini desteklemekte, böylece metanojenik popülasyonların ekolojik rekabet gücünü sınırlandırmaktadır (Firkins ve Mitchell, 2023; Shang ve ark., 2026). Buna paralel olarak, rasyona dahil edilen selülaz ve hemiselülaz gibi dış kaynaklı (eksojen) enzimler, yapısal karbonhidratların sindirilebilirliğini artırarak hammadde (substrat) kullanım etkinliğini iyileştirmekte ve metan üretimine zemin hazırlayan verimsiz fermantasyon süreçlerini devre dışı bırakabilmektedir (Kılıç ve Boğa, 2021).

Söz konusu stratejiler, ruminantların besin maddesi biyoyararlanımını artırarak yemden yararlanma oranlarını (YYO) iyileştirmekte, üretim maliyetlerini düşürürken çevresel ayak izini küçültmektedir (Roques ve ark., 2023). "Altın Oran" yaklaşımı ve bütünleşik fonksiyonel besleme yöntemleri, hayvansal üretimde verimlilik ve ekolojik sürdürülebilirlik hedeflerinin sabit bir sistem içinde yönetilmesine imkan tanımaktadır. Ancak bu yaklaşımların etkinliği; mikrobiyal ekosistem yönetimi, katkı maddesi etkileşimleri (sinerjileri) ve sindirim hızının kapsamlı ve sistemli bir modelleme ile iyileştirilmesine bağlıdır. Gelecekte, bu modelin mikroorganizma tabanlı hassas hayvancılık sistemleri (Precision Livestock Farming) ile eklemlenmesi, metan azaltımı ve üretim çıktıları açısından daha öngörülebilir ve sürdürülebilir bir hayvancılık rejimi sağlayacaktır.

7. Metan Emisyonu ve Sera Gazı Azaltım Potansiyeli

Ruminant kaynaklı enterik metan (*CH4*) salınımları, karbondioksite oranla çok daha yüksek küresel ısınma potansiyeline sahip olması nedeniyle, iklim değişikliğiyle mücadelede öncelikli bir çevresel ölçüt olarak kabul edilmektedir (Morshidy, 2025). Besleme müdahaleleri yoluyla metan salınımının kontrol altına alınması, yalnızca ekolojik yükün hafifletilmesi değil, aynı zamanda işkembe (rumen) enerji kaybının önüne geçilerek hayvansal üretim verimliliğinin en üst düzeye çıkarılması açısından stratejik bir öneme sahiptir (Boran ve Serbester, 2022). Bu doğrultuda; fitobiyotikler, tanenler, saponinler ve esansiyel yağlar gibi bitkisel ikincil bileşenler, işkembe fermantasyon hızını düzenleyerek metan üreten aktiviteyi doğrudan veya dolaylı yollarla engelleme potansiyeli taşımaktadır (Min ve ark., 2020).

Tanenlerin metan oluşumu üzerindeki baskılayıcı etkisi; selüloz parçalayan mikroorganizmaların aktivitesini sınırlandırarak metan oluşumunun temel hammaddeleri olan hidrojen (H_2) ve karbondioksit (CO_2) arzını azaltması, ayrıca metanojenik arkeler ve protozoa popülasyonları üzerinde hücre yıkımlayıcı etki yaratması ile açıklanmaktadır (Arslan, 2017). Literatürde, özellikle bağlı (kondanse) tanen içeren yem kaynaklarının, metan üreten aktiviteyi doğrudan baskılayarak salınım düzeylerinde %13–16 bandında bir azalma sağlayabildiği rapor edilmektedir (Kumar ve ark., 2023). Eş zamanlı olarak, probiyotikler ve mikrobiyal yem katkıları, işkembe mikroflorasını dengeleyerek fermantasyon biçimini (profilini) propiyonat yönünde en uygun hale getirmekte ve metan üreten mikroorganizmaların rekabetçi üstünlüğünü sınırlandırmaktadır (Ncho ve ark., 2024; Saleem ve ark., 2025).

Kimyasal müdahaleler kategorisinde, 3-nitrooksipropanol (3-NOP) gibi özel engelleyiciler, metan oluşumunun son aşamasındaki enzim sistemlerini doğrudan hedef alarak köklü bir salınım düşüşü sağlama kapasitesine sahiptir (Malyugina ve ark., 2025). Ancak bu tür yapay engelleyicilerin ticari kullanımında; uzun vadeli metabolik etkiler, maliyet-etkinlik mantığı ve gıda güvenliği kurallarına uyum gibi unsurlar titizlikle analiz edilmelidir (Palangı ve Lackner, 2022).

Alternatif bir yaklaşım olarak, rasyonun enerji yoğunluğunu artıran yağ takviyeleri ve biyolojik olarak aktif bitkisel kimyasalların kombinasyonu, hem salınım kontrolü hem de hayvansal (zooteknik) performansın iyileştirilmesi açısından ortak etkileşimli bir model sunmaktadır (Kılıç ve Boğa, 2021). Özellikle saponinler, işkembe ekosistemini değiştirerek metan oluşumunu baskılarken, enerjinin metan yerine üretim çıktılarına yönlendirilmesini teşvik ederek yemden yararlanma verimliliğini en üst düzeye çıkarabilmektedir (Malyugina ve ark., 2025).

Enterik metan azaltım stratejileri; bitkisel, mikrobiyal ve kimyasal yaklaşımların harmanlandığı çok boyutlu bir sistem dinamiğini temsil etmektedir. Bu müdahalelerin başarısı, yalnızca salınım verilerindeki sayısal düşüşle değil, aynı zamanda işkembe mikrobiyal dengesinin korunması ve hayvan refahı standartlarının sürdürülmesiyle ölçülmelidir. Dolayısıyla, gelecekteki modellerin sürdürülebilirlik, biyolojik güvenlik ve ekonomik uygulanabilirlik arasındaki hassas dengeyi gözeten bütünleşik besleme rejimlerine odaklanması elzemdir.

8. Ekonomik Analiz

Ruminant besleme rasyonlarında öngörülen stratejik değişimlerin ekonomik sürdürülebilirliği; doğrudan yem maliyetleri, hayvansal performans ölçütleri ve dolaylı çevresel kazanımları içeren kapsamlı ve sistemli bir bakış açısıyla analiz edilmelidir. Bu bağlamda; metan (*CH4*) emisyonunu düşüren özel yem katkılarının tedarik ve uygulama maliyetleri ile nihai ürün (et, süt) verimliliğindeki marjinal değişimler arasında hassas bir ekonomik dengenin kurulması kritik bir gerekliliktir (Muruz ve Sertkaya, 2022). Bu yaklaşımların karbon piyasalarıyla entegre edilmesi, çevresel performansı ekonomik bir kazanca dönüştürecektir. Bu durum, üreticilere sunulan finansal teşvikler yoluyla sürdürülebilir üretim modellerinin sahada benimsenme hızını artıracaktır. Bu makro-ekonomik çerçeve, üretim maliyetlerinin en aza indirilmesinin yanı sıra, çevresel düzenlemelere uyumlu yeni iş modellerinin ve sürdürülebilir pazar fırsatlarının oluşmasına zemin hazırlamaktadır.

Bu doğrultuda, deniz yosunları (makroalgler) ve 3-nitrooksipropanol (3-NOP) gibi yeni nesil engelleyicilerin metan oluşumunu baskılama potansiyelleri ile teknik-ekonomik uygulanabilirlikleri, mevcut araştırma gündeminin öncelikli eksenlerini oluşturmaktadır (Muruz ve Sertkaya, 2022). Özellikle *Asparagopsis* türü deniz yosunlarının rasyona düşük katılım oranlarında dahi enterik metan üretimini çarpıcı düzeyde azalttığı raporlanmıştır. Ancak, bu tür yenilikçi bileşenlerin endüstriyel ölçekte uyarlanması; birim maliyet, gıda güvenliği standartları, tüketici algısı ve yasal mevzuatlar gibi çok katmanlı değişkenlerin en uygun hale getirilmesini zorunlu kılmaktadır (Malyugina ve ark., 2025). Bu nedenle, yem katkı maddelerinin doz-yanıt ilişkilerinin belirlenmesi ve işletme kârlılığı üzerindeki net etkilerinin modellenmesi amacıyla, uzun dönemli ve geniş kapsamlı canlı (*in vivo*) saha denemelerine ihtiyaç duyulmaktadır (Boğa ve ark., 2021).

Metan emisyonlarının azaltılması, çevresel bir ödevden ziyade; hayvancılık işletmelerinde ekonomik akılcılık ve biyolojik etkinliği birleştiren stratejik bir sistem mühendisliği yaklaşımıdır. Mevcut literatürdeki temel kısıt, biyolojik etkinliği yüksek olan özel engelleyicilerin ve deniz yosunlarının, ölçeklenebilirlik ve maliyet-etkinlik ölçütleri açısından geleneksel (konvansiyonel) hayvancılık sistemlerine tam eklemlenmesinde yaşanan aksaklıklardır. Dolayısıyla, gelecekteki araştırmaların yalnızca metabolik etkinliğe odaklanmak yerine; saha koşullarındaki operasyonel uygulanabilirlik, yatırımın geri dönüş oranı (ROI) ve uzun vadeli sistemik sürdürülebilirlik modellerini içeren disiplinler arası yaklaşımlara yoğunlaşması elzemdir.

9. Sürdürülebilirlik ve İklim Değişikliği Perspektifi

Ruminant üretim sistemlerinin çevresel sürdürülebilirliği, küresel iklim değişikliği ile mücadele stratejilerinde belirleyici bir ölçüt olarak kabul edilmektedir. Bu doğrultuda, rasyon iyileştirmesi ve yem sinerjileri temelinde geliştirilen besleme stratejileri, enterik metan (CH_4) salınımlarını baskılayarak hayvansal üretimin sera gazı yoğunluğunu düşürme ve sektörel ekolojik dengeyi koruma potansiyeline sahiptir (Yıldırım, 2024). Düşük karbonlu tarım modelleri kapsamında yenilikçi besleme çözümlerinin yaygınlaşması, tarımsal sistemlerin çevresel başarısını artırmanın yanı sıra, küresel pazardaki tüketici talepleri ve ekonomik sürdürülebilirlik açısından stratejik bir zorunluluktur (Cardoso ve Gimenes, 2024).

Literatürde, 3-nitrooksipropanol (3-NOP) gibi özel enzim engelleyicilerin ticari ölçekteki kullanımı, özellikle sığırlarda metan salınımını azaltmada dikkate değer bir etkinlik sergilemektedir (Alemu ve ark., 2021; Hristov, 2024). Bununla birlikte, söz konusu

engelleyicilerin uzun dönemli biyolojik etkileri, işkembe uyum süreçleri ve büyük ölçekli eklemlenmedeki lojistik kısıtlar henüz tam olarak aydınlatılamamıştır (Malyugina ve ark., 2025). Benzer şekilde, bromoform içeriği yüksek deniz yosunlarının (makroalglerin), özellikle meraya dayalı üretim sistemlerinde metan oluşumunu baskılamadaki rolü güncel bir araştırma odağıdır (Meo-Filho ve ark., 2024). Ancak bu uygulamaların mekanistik temellerinin, gıda güvenliği kuralları ve çevresel risk analizleri çerçevesinde daha kapsamlı doğrulanması gerekmektedir (Wasson ve ark., 2023). Ayrıca, laboratuvar çalışmalarıyla (in vitro) raporlanan bitkisel kimyasal (fitokimyasal) sinerjilerin, canlı hayvan (in vivo) koşullarındaki rasyon etkileşimleri ile kanıtlanması, bu alandaki bilimsel boşlukların kapatılması açısından elzemdir (Dillon ve ark., 2021).

Sonuç olarak, metan azaltımına yönelik besleme müdahaleleri, yalnızca teknik bir salınım kontrol aracı değil, sürdürülebilir hayvancılık sistemlerinin yapısal dönüşümü için temel bir bileşendir. Mevcut sınırlılıklar değerlendirildiğinde; 3-NOP ve deniz yosunu gibi yüksek potansiyelli teknolojilerin maliyet etkinliği, ölçeklenebilirliği ve uzun vadeli fizyolojik etkileri bakımından henüz gelişim evresine ulaşmadığı görülmektedir. Dolayısıyla, gelecek araştırmaların yalnızca salınım verileri üzerine değil; sistem düzeyinde uygulanabilirlik, ekonomik akılcılık ve ekolojik risk değerlendirmelerini içeren disiplinler arası bir bakış açısına odaklanması gerekmektedir.

10. Sonuç ve Öneriler

Literatür, ruminant beslemede "Altın Oran" ve "Yem Sinerjisi" yaklaşımlarının; hayvan performansı, ekonomik kârlılık ve iklim değişikliğiyle mücadele ekseninde stratejik bir öneme sahip olduğunu göstermektedir. Yapılan analizler, kaba ve kesif yem dengesinin en uygun hale getirilmesi, alternatif yerel yem kaynaklarının rasyona eklemlenmesi ve fonksiyonel bileşenlerin kullanımıyla üretim verimliliğinin artırılabileceğini ve çevresel ayak izinin en aza indirilebileceğini göstermektedir (Ahmed ve ark., 2024). Özellikle hassas besleme yöntemleri ve algılayıcı teknolojilerin devreye alınması, besin madde gereksinimlerinin hassasiyetle karşılanmasını sağlayarak yem kullanım etkinliğini artırmakta ve metan salınımlarını baskılamaktadır (Şonea ve ark., 2023).

Metan azaltımında 3-nitrooksipropanol gibi özel engelleyiciler ve yosun türleri gibi yenilikçi katkı maddeleri güçlü birer araç olarak öne çıksa da, bu maddelerin işkembe mikroorganizma topluluğu (rumen mikrobiyomu) üzerindeki uzun vadeli etkileri ve farklı genetik hatlardaki farklılıkları hâlâ derinlemesine araştırma gerektiren alanlardır (Cardoso ve Gimenes, 2024; Orzuna-Orzuna ve ark., 2024; Ayemele ve ark., 2025). Mevcut bulgular ışığında, sürdürülebilir bir hayvancılık modeli için şu stratejik yaklaşımlar önerilmektedir:

Bütünleşik (Entegre) Rasyon Yönetimi: Metan azaltımı tek bir katkı maddesine indirgenmemeli; kaba yem parçalanabilirliğinin artırılması, enerji yoğunluğunun iyileştirilmesi ve tanen/saponin gibi doğal bitkisel bileşenlerin (fitobiyotiklerin) kullanımıyla kapsamlı ve sistemli bir model tasarlanmalıdır (Koyuncu ve Akgün, 2018; Kılıç ve Boğa, 2021).

Genetik ve Besleme Etkileşimi (İnteraksiyonu): Düşük metan salınımına sahip bireylerin genetik seçimle (genomik seleksiyonla) belirlenmesi, besleme stratejileriyle birleştirilerek kalıcı ve birikimli bir azaltım stratejisine dönüştürülmelidir (Qin ve ark., 2025; Assan, 2025).

Mikrobiyom Odaklı Yaklaşımlar: Hidrojen akışını metan oluşumu yerine alternatif metabolik yollara yönlendirecek yeni nesil probiyotik ve yağ (lipit) bazlı stratejilerin moleküler işleyişleri daha ayrıntılı analiz edilmelidir (Qi ve Feng, 2024; Wang ve ark., 2025).

Sosyoekonomik Uygulanabilirlik (Fizibilite): Geliştirilen teknolojilerin ticari işletmelerde kabul görmesi için kapsamlı maliyet-fayda analizleri yapılmalı ve üretici uyumunu destekleyecek modeller geliştirilmelidir (Chakma ve ark., 2025).

Sonuç olarak, ruminant beslemede çevresel ve ekonomik hedefler artık birbirinden bağımsız unsurlar değil, birlikte iyileştirilmesi gereken tek bir sistem problemidir. Gelecekteki çalışmalar; teknik etkinliğin ötesine geçerek; genetik, mikrobiyom ve rasyon değişimlerinin ortak etkilerini uzun vadeli saha verileriyle modellemeye odaklanmalıdır. Sürdürülebilir bir hayvansal üretim, ancak bu disiplinler arası yaklaşımların pratik ve ekonomik uygulanabilirliği ile mümkün olacaktır.

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YAPAY ZEKÂ KULLANIM BEYANI

Bu çalışma kapsamında literatür taslağının oluşturulması ve metin dilinin akademik olarak düzenlenmesi aşamalarında yalnızca yardımcı araç olarak yapay zekâ tabanlı yazım destek sistemlerinden yararlanılmıştır. Bununla birlikte, çalışmanın bilimsel içeriği, analizleri, yorumları ve nihai metni tamamen yazar(lar)a aittir. Tüm bilimsel sorumluluk yazar(lar) üzerinde olup, yapay zekâ araçları hiçbir şekilde araştırmanın bilimsel karar mekanizmalarında belirleyici olmamıştır.

THE EFFECT OF NANOPARTICLE APPLICATION ON SECONDARY METABOLITE PRODUCTION IN THE 'MICHELE PALIERI' GRAPE CULTIVAR

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Abstract

In recent years, environmentally friendly approaches that both enhance yield and regulate plant growth and development without leaving harmful residues have gained increasing attention in the agricultural sector. Nanotechnological methods represent one of these innovative approaches and their application in agriculture is referred to as phytotechnology. Nanoparticles (NPs) have been reported to exert positive effects, particularly under stress conditions. Accordingly, studies investigating the use of NPs to mitigate the adverse effects of abiotic stresses such as high temperature, salinity, drought, and heavy metal toxicity have increased significantly. In this study, the effects of selenium dioxide (SeO_2) nanoparticle applications on secondary metabolite accumulation in the 'Michele Palieri' grape cultivar were investigated. The experiment was conducted in a 9-year-old vineyard consisting of 'Michele Palieri' grapevines grafted onto 1103 Paulsen rootstock. NP applications were performed at three different phenological stages: berry set, veraison, and 10 days before harvest, at four concentrations (0 (control); 50; 100; 150 ppm). Cluster samples were collected during the ripening period. Total phenolic compounds, total flavanols, and total flavonols were determined spectrophotometrically, while individual phenolic compounds and plant hormones were identified using HPLC analysis. Among the phenolic compounds, gallic acid, 3,4-dihydroxybenzoic acid, chlorogenic acid, 2,5-dihydroxybenzoic acid, vanillic acid, caffeic acid, epicatechin, p-coumaric acid, ferulic acid, rutin, ellagic acid, cinnamic acid, quercetin, and resveratrol were quantified. In addition, plant hormones including gibberellic acid, zeatin, abscisic acid, and salicylic acid were analyzed. The results indicated that nanoparticle applications had positive effects on enhancing secondary metabolite production, although the magnitude of the effect varied depending on the applied NP dose.

Keywords: Nanotechnology, Grapevine, Grape, Phenolic compounds, Phytohormones

MICHELE PALIERI ÜZÜM ÇEŞİDİNDE NANOPARTİKÜL UYGULAMASININ SEKONDER METABOLİT ÜRETİMİ ÜZERİNE ETKİSİ

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Özet

Son yıllarda tarım sektöründe yapılan çalışmalarda bir taraftan verim artışı sağlayan, bir taraftan da kalıntı etkisi olmaksızın bitkide büyüme ve gelişmeyi düzenleyen çevreci yaklaşımlar öne çıkmaktadır. Nanoteknolojik yöntemler de bunlardan birisidir. Nanoteknolojik yöntemlerin tarımda kullanılması "Fitonanoteknoloji" olarak tanımlanmaktadır. Nanopartikül (NP) lerin özellikle stres üzerinde olumlu etkiler gösterdiği belirlenmiştir. Yüksek sıcaklık, tuzluluk, kuraklık ve ağır metal toksisitesi gibi abiyotik stres koşulları altında stresin olumsuz etkilerini azaltmada NP kullanımına yönelik çalışmalar her geçen gün artmaktadır. Bu araştırma ile de Michele Palieri üzüm çeşidinde bir NP olan SeO2 uygulamalarının tanelerde sekonder metabolit birikimi üzerine etkileri incelenmiştir. Uygulamalar 1103 Paulsen Amerikan asma anacı üzerine aşılanmış Michele Palieri üzüm çeşidinden oluşan 9 yaşındaki bağda gerçekleştirilmiştir. Tanelerin koruk safhasında, ben düşme döneminde ve hasattan 10 gün önce olacak şekilde 3 ayrı dönemde ve 0 (kontrol); 50; 100 ve 150 ppm olmak üzere dört dozda NP SeO_2 uygulanmıştır. Olgunlaşma döneminde salkım örnekleri alınmış, toplam fenolik bileşik, toplam flavanol ve toplam flavonol analizleri (spektrofotometrik) ile fenolik bileşiklerin ve bitkisel hormonların tanımlanması (HPLC) yapılmıştır. Fenolik bileşikler içerisinden gallik asit, 3,4-dihidroksi benzoik asit, klorogenik asit, 2,5- dihidroksi benzoik asit, vanilik asit, kafeik asit, epikateşin, p-kumarik asit, ferulik asit, rutin, ellajik asit, sinnamik asit ve kuersetin ile resveratrol miktarları tespit edilmiştir. Bitkisel hormonlar içerisinde ise gibberellik asit, zeatin, absisik asit ve salisilik asit miktarları belirlenmiştir. Araştırma sonucunda uygulanan NP dozuna göre değişmekle birlikte NP'lerin sekonder metabolit üretimini artırmada olumlu etkilerinin bulunduğu belirlenmiştir.

Anahtar Kelimeler: Nanoteknoloji, Asma, Üzüm, Fenolik bileşik, Fitohormon

1. Giriş

Günümüzde tıp, kimya, ilaç, gıda, kozmetik, tekstil, tarım, çevre, enerji, elektronik ve ulaşım gibi çeşitli alanlarda kullanımı söz konusu olan nanoteknoloji (Rai ve Ingle, 2012; Judy ve Bertsch, 2014; Woldeamanuel et al., 2021), geleneksel mikroskoplarla görüntülenemeyecek kadar küçük bir ölçü birimi olan nano düzeyinde geliştirilen, 1 ile 100 nanometre arasında değişen birimlerde gerçekleştirilen teknolojiler olarak tanımlanmaktadır. Küçük boyutlu olması, aynı etkinin daha küçük hacimlerde alınabilmesi, yavaş bir salınım göstererek pek çok yönden toksisitenin önüne geçilebilmesi ile büyük avantajlar sunan bir tekniktir. Böylece ürünler daha etkin, işlevsel ve dayanıklı hale getirilmekte, ayrıca enerji ve hammadde tasarrufu sağlanmaktadır. (Kuzma ve Verhage, 2006; Iravani et al., 2014).

Nanoteknolojik yöntemlerin tarımda kullanılması "Fitonanoteknoloji" olarak tanımlanmaktadır. (Wang et al., 2016; Fincheira et al., 2019). Tarım sektöründe nanoteknolojik yöntemler tohum çimlenme aşamasından başlayarak fide-fidan gelişim dönemleri ve sonrasında verim dönemleri olmak üzere çok farklı dönemlerde başarıyla kullanılmaktadır (Kamle et al., 2020). Bu teknolojinin tarımsal alanda kullanımının her geçen gün arttığı bilinmektedir (Chauhan et al., 2020; Usman et al., 2020; Yadav et al., 2020).

Yer kabuğunda nadir bulunan bir lantanit olan seryum oksit (CeO_2) fizik, kimya, biyoloji ve malzeme bilimi gibi alanlarda kullanımı olan bir elementtir. (Xu ve Qu, 2014, Cotruvo, 2019). Nanoteknoloji ile elde edilmiş CeO_2 ise biyomedikal ve bitki uygulamalarının yanı sıra, katı oksit yakıt hücrelerinde, katalitik ve fotokatalitik uygulamalarda yaygın olarak kullanılmaktadır (Cotruvo, 2019).

Bitkiler içerdikleri çoğu bileşenler ile insan sağlığı üzerinde çeşitli yönde etkiler göstermektedir. Nanoteknolojik ürünlerin bir diğer kullanım alanı da bitkilerdeki bu bileşenlerin sentezi üzerinde etki göstermeleridir. Bu kullanım şekli ile bitkide bulunan bileşenlerin sentezi artırılma potansiyeli söz konusu olmaktadır. Asmada sekonder metabolit birikimini artırmaya yönelik NP uygulaması ile ilgili bir çalışmaya rastlanmamıştır. Bu araştırma ile renkli, sofralık bir üzüm çeşidi olan Michele Palieri üzüm çeşidinde CeO2 NP uygulamalarının tanelerde sekonder metabolit birikimi üzerine etkisi incelenmiştir.

2. Materyal ve Yöntem

Araştırma, 2025-2026 yılları arasında yürütülmüştür. Uygulamalar Yozgat Merkez Köylerinden olan Recepli Köyü'nde 5 da arazi üzerine tesis edilmiş, 1103 Paulsen Amerikan asma anacı üzerine aşılanmış Michele Palieri üzüm çeşidinden oluşan 9 yaşındaki bağda yapılmıştır. Uygulamalar, çeşidin fenolojik gözlemleri baz alınarak tanelerin koruk safhasında, ben düşme döneminde ve hasattan 10 gün önce olacak şekilde 3 ayrı dönemde yapılmıştır. CeO_2 NP uygulaması birisi kontrol olmak üzere 50, 100 ve 150 mg/L konsantrasyonda uygulanmıştır. Olgunlaşma döneminde salkım örnekleri alınmış, taze olarak yapılması gereken analizler hemen yapılmış, diğer analizler için ise örnekler derin dondurucuya yerleştirilmiştir. Analizlerin bir kısmı Yozgat Bozok Üniversitesi Ziraat Fakültesi Bahçe Bitkileri Bölüm Laboratuvarında, bir kısmı ise Burdur Mehmet Akif Ersoy Üniversitesi Bilimsel ve Teknoloji Uygulama ve Araştırma Merkezi'nde yapılmıştır.

2.1. Fenolik bileşik ekstraksiyonu

Fenolik madde ekstraksiyon işlemleri Caponio et al. (1999)'nin metoduna göre yapılmıştır. Elde edilen ekstrakt daha sonra toplam fenolik bileşik, toplam flavonol, toplam flavanol ve HPLC de fenolik bileşiklerin belirlenmesi amacıyla kullanılmıştır.

Toplam fenolik bileşik miktarları Folin Ciocalteu kolorimetrik metodu kullanılarak Singleton ve Rossi (1965)'ye göre yapılmış, gallik asit eşdeğeri (Gallic Acid Equivalent, GAE) olarak sunulmuştur. Toplam flavonoller Neu solusyonu kullanılarak Dai et al. (1995)'ne göre yapılmıştır. Rutin eşdeğeri olarak (Rutin Equivalent, RE) mg/g şeklinde sunulmuştur. Toplam flavanoller Arnous et al. (2001)'ne göre DMAC (dimetil amino sinnamaldehit) metodu kullanılarak gerçekleştirilmiş, kateşin eşdeğeri (Catechin Equivalent, CE) (mg/g) cinsinden sunulmuştur.

2.2. Fenolik bileşiklerin ve bitkisel hormonların HPLC'de tanımlanması

Bu amaçla modifiye edilmiş Caponio et al. (1999)'nin yöntemi kullanılmıştır. Fenolik bileşikler içerisinden asmada ve üzümde en fazla bulunan gallik asit, 3,4-dihidroksi benzoik asit, klorogenik asit, 4-dihidroksi benzoik asit, vanilik asit, kafeik asit, epikateşin, p-kumarik asit, ferulik asit, rutin, ellajik asit, sinnamik asit ve kuersetin ile resveratrol miktarları; bitkisel hormonlar içerisinde ise gibberellik asit, zeatin, absisik asit, salisilik asit ve indol asetik asit miktarları belirlenmiştir.

2.3. Verilerin değerlendirilmesi

Araştırma 3 tekerrürlü ve her tekerrürde 5 omca olacak şekilde yürütülmüştür. Deneme sonunda elde edilen veriler tesadüf blokları deneme desenine göre SPSS 20 istatistik programında değerlendirilmiş, ortalamalar arasındaki farklılıklar Duncan çoklu karşılaştırma testine göre belirlenmiştir ($p \leq 0,05$).

3. Bulgurlar ve Tartışma

Farklı dozlarda CeO_2 NP'nin asmada sekonder metabolit üretimi üzerine etkisinin incelendiği bu araştırmada toplam fenolik bileşik içeriği bakımından 150 mg/L; toplam flavonol ve toplam flavonol içeriği bakımından ise 100 mg/L CeO2 NP dozunun daha etkili olduğu görülmektedir (Çizelge 1).

Çizelge 1. Spektrofotometrik olarak belirlenen fenolik bileşik miktarları

CeO_2 NP (mg/L)	Toplam fenolik madde (mg/g GAE)	Toplam flavonol (mg/g RE)	Toplam flavanol (mg/g CE)
Kontrol	1,742* c	0,019 b	0,013 c
50	2,828 b	0,034 b	0,023 b
100	5,117 a	0,082 a	0,038 a
150	6,048 a	0,048 b	0,021 b

*Aynı sütunda farklı harflerle gösterilen ortalamalar arasında istatistiksel olarak farklılık bulunmaktadır ($p<0.05$).

Çizelge 2. HPLC ile belirlenen fenolik bileşik miktarları (ppm)

CeO_2 NP (mg/L)	Kateşin	Ellajik asit	Epikateşin	Gallik asit	3,4 dihidroksi benzoik asit	4-hidroksi benzoik asit	Kafeik asit	Naringin	Sinnamik asit	Vanilik asit	p-kumarik asit	Ferulik asit	Klorogenik asit	Rutin	Kuersetin	Resveratrol

Kontrol	1,848 b*	93,841 c	23,692 b	0,021 b	0,054 b	0,099	23,097 c	1,467 a	0,078 a	0,164 b	0,261 b	0,548 a	0,028 a	17,538 c	1,719 a	0,285 a
50	1,847 b	126,026 bc	1,306 c	0,021 b	0,046 b	0,108	133,842 b	0,772 bc	0,126 b	0,445 a	0,753 a	0,462 b	0,023 b	71,248 b	1,373 b	0,197 c
100	2,101 a	303,323 a	19,831 b	0,024 a	1,042 a	0,099	170,428 a	0,696 c	0,128 b	0,436 a	0,728 a	0,360 d	0,029 a	73,873 a	1,488 b	0,245 b
150	1,888 b	186,397 b	56,035 a	0,021 b	0,732 a	2,755	7,710 d	0,960b	0,297 a	0,118 c	0,041 c	0,383 c	0,026 ab	17,751 c	1,792 a	0,293 a

*Aynı sütunda farklı harflerle gösterilen ortalamalar arasında istatistiksel olarak farklılık bulunmaktadır ($p<0.05$).

HPLC ile belirlenen fenolik bileşiklerin, uygulanan CeO_2 NP dozuna göre değişiminin sunulduğu Çizelge 2 incelendiğinde; vanillik asit ve p-kumarik asit sentezinin en yüksek seviyelerinin 50 mg/L dozunda CeO_2 NP uygulanan omcalardaki salkımlardan elde edildiği dikkati çekmektedir. Kateşin, ellajik asit, gallik asit, 3,4-dihidroksi benzoik asit, kafeik asit, klorogenik asit ve rutin içeriklerinin 100 mg/L CeO_2 NP dozunda en yüksek seviyelerde sentezlendikleri görülmektedir. En yüksek doz olan 150 mg/L CeO_2 NP dozunda ise epikateşin, 4-hidroksi benzoik asit, sinnamik asit, kuersetin ve resveratrol en yüksek seviyede sentezlenmişlerdir (Çizelge 2).

Araştırmada bitkisel hormonlar içerisinden zeatin, salisilik asit, gibberellik asit, indol asetik asit ve absisisk asit'in de CeO_2 NP uygulamaları karşısındaki değişimi incelenmiştir. Çizelge 3 incelendiğinde, özellikle 100 mg/L dozunun zeatin, salisilik asit ve indol asetik asit birikiminde etkili bir uygulama dozu olduğu görülmektedir.

Çizelge 3. HPLC ile belirlenen bitkisel hormon miktarları (ppm)

CeO_2 NP (mg/L)	Zeatin	Salisilik Asit	Gibberellik Asit (GA_3)	Indol Asetik Asit (IAA)	Absisik Asit (ABA)
Kontrol	98,255 c*	0,553 c	126,231 a	422,625 d	0,039 c
50	112,966 b	0,277 d	63,958 d	1462,636 b	10,653 a
100	550,563 a	2,174 a	69,385 c	2054,272 a	10,542 a

150	105,600 bc	1,165 b	95,854 b	762,188 c	1,263 b

*Aynı sütunda farklı harflerle gösterilen ortalamalar arasında istatistiksel olarak farklılık bulunmaktadır ($p<0.05$).

4. Tartışma ve Sonuç

Bitkiler içerdikleri çoğu bileşenler ile insan sağlığı üzerinde çeşitli yönde etkiler göstermektedir. Nanoteknolojik ürünler bitkilerdeki bu bileşenlerin sentezi üzerinde etki göstermektedirler. Nano-elisitör olarak genel bir tanım ile adlandırılan bu kullanım şekli ile bitkide bulunan bileşenlerin sentezi artırılarak insan sağlığı üzerine olan olumlu etkilerinden daha fazla yararlanılabilme potansiyeli söz konusu olmaktadır.

Aynısefa (*Calendula officinalis* L.) bitkisi üzerinde yapılan bir çalışma, CeO_2 NP'lerinin yapraklara yüksek dozda uygulanması (3200 mg/L) ile sürgünlerde NP birikiminin olduğu, sürgün uzunluğunun azaldığı ve toksik etkilere neden olduğu gösterilmiştir. Düşük dozlarda ise (100 mg/L) sürgün uzunluğu ve taze ağırlığı artırmıştır (Jahani et al., 2019). Farklı amiloz seviyelerine sahip üç çeltik çeşidinde Ce akümülasyonu ile pirinç tanelerindeki antioksidan seviyelerinin, nişasta içeriğinin, mineral besin içeriklerinin ve organik bileşiklerin azaldığı belirlenmiştir. 500 mg/kg CeO_2 NP'nin toprağa uygulanması ile pirinç tanelerinin kalitesi düşmüştür (Rico et al., 2013). Benzer şekilde arpada farklı dozlarda (125, 250 ve 500 mg/kg) CeO_2 NP'lerinin uygulaması ile düşük dozlarda büyüme ve gelişmenin sağlandığı, mineral besin içeriği ve amino asit seviyelerinin arttığı, 500 mg/kg'lık yüksek dozda ise verimin düştüğü tespit edilmiştir (Rico et al., 2015).

Jasim et al. (2017), AgNP uygulamalarının, *Trigonella foenum-graecum* (çemen otu) bitkisinde birer sekonder metabolit olan diosgenin içeriğini artırdığını ifade etmişlerdir. Nanede bakır nanopartikülerin kullanıldığı bir araştırmada ise kamfen, phellandrene ve limonen seviyeleri artırılmıştır (Lafmejani et al., 2018). Benzer şekilde Ramezannezhad et al. (2019), ekinezya (*Echinacea purpurea*)' nın in vitro hücre süspansiyon kültürlerinde şikorik asit üretimini ciddi anlamda artırdığını; Karakas (2020) ise çivit otu bitkisinde aynı zamanda birer boya maddesi olarak kullanım alanı olan indigo ve triptantrin konsantrasyonlarının artırılmasına önemli katkılar sağladığını ortaya koymuşlardır. Bu bileşenlerin farklı nanoteknolojik uygulamalarla artırılabildiğine ilişkin farklı bitkilerde çalışmalar

sürdürülmektedir (Ghasemi et al., 2015; Tian et al., 2018; Rezai et al., 2019; Lala, 2020; Rahimi et al., 2020).

Bağcılıkta NP'ler üzerinde sınırlı sayıda olan çalışmanın ilkinde Flame Seedless çeşidine ait fidanların tuza dayanımı üzerine CeO_2 NP'nin etkisi incelenmiştir. 25, 50 ve 100 mg/L düzeyinde CeO_2 NP'nin, iki farklı tuz konsantrasyonuna (25 ve 75 mM NaCl) maruz bırakılan asma çeliklerinde biyokimyasal özellikler üzerine etkisini incelemişlerdir. Araştırma sonucunda genel olarak CeO_2 NP'leri ile yapılan uygulamanın tuz stresinin (75 mM NaCl) olumsuz etkilerini hafiflettiği, yüksek tuzluluk seviyelerinde klorofil hasarını önemli ölçüde iyileştirdiği, daha düşük prolin, MDA ve EL seviyeleriyle tuzluluk kaynaklı hasarların hafifletildiği ifade edilmiştir. Ayrıca kontrol bitkileriyle karşılaştırıldığında GP, APX ve SOD gibi antioksidan enzim aktivitelerinde önemli artışların olduğu da vurgulanmıştır. Bu bulguları ile araştırmacılar CeO_2 NP'lerinin asmada umut verici tuz stresi giderici maddeler olarak kullanılabileceğine işaret etmişlerdir (Gohari et al., 2021). Asmadaki bir diğer çalışma kuraklık stresi üzerine CeO2 NP'nin etkisini inceleyen bir çalışmadır. Superior Seedless üzüm çeşidine ait fidanlarda yapraktan uygulanan CeO_2 NP (0, 5, 50 ve 500 mg/L)'nin kuraklık stresi üzerine etkisi incelenmiştir. 50 mg/L CeO_2 NP'ler kuraklık stresi altındaki asma fidanlarının agronomik özelliklerini (sürgün uzunluğu, yaprak alanı, sürgün ve kök kuru ağırlıkları) ve fotosentetik parametrelerini (stoma iletkenliği, klorofil a ve klorofil b) önemli ölçüde iyileştirmiştir. Ayrıca SOD, CAT ve APX aktivitesinin önemli ölçüde indüklendiği belirtilmiştir (Daler, 2024).

Yapılmış olan bu araştırma ile de Michele Palieri üzüm çeşidinde CeO_2 NP uygulamalarının birer sekonder metabolit olan fenolik bileşenler ile hormon içerikleri üzerine etkisi incelenmiş olup, elde edilen sonuçlar, bu bileşiklerin söz konusu alanda kullanım potansiyelinin yüksek olduğunu göstermektedir.

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SUSTAINABLE VITICULTURE AND LOCAL DEVELOPMENT IN BAHADIN TOWN (SORGUN/YOZGAT PROVINCE): A SURVEY STUDY

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Abstract

This study aimed to determine the viticulture potential of Bahadın town, located in the Sorgun district of Yozgat province, Türkiye. The research was conducted using a structured survey approach. Data were collected through face-to-face interviews with 30 grape producers using a questionnaire consisting of 37 items. The questionnaire was designed to identify the producers' demographic characteristics, vineyard area, farm structure, viticulture techniques and cultural practices, yield, marketing, economic perceptions, and support mechanisms.

Among the producers included in the survey, 46.43% were women and 53.57% were men. The majority of both women (17.86%) and men producers were aged 50 years and above. A considerable proportion of women producers (28.57%) reported that although they owned vineyards, yields had declined due to their inability to adequately perform necessary technical and cultural practices. All women participants aged 40 years and above expressed their willingness to establish new vineyards. Similarly, all men producers aged 40 years and above reported owning vineyard areas of 10 decares or more and stated that they were also willing to establish new vineyards.

All respondents indicated that viticulture is a profitable agricultural activity due to its suitability for various processing techniques; however, they emphasized that they have not been able to achieve this profitability due to insufficient technical knowledge.

The participants were aware of their knowledge gaps in key areas such as planting, pruning and training, irrigation, pest and disease management, and fertilization, and were identified as being open to acquiring and applying new knowledge. As a result of the survey, producers emphasized the importance of both establishing new modern vineyards with standard varieties and preserving and maintaining traditional varieties that are on the verge of disappearing in the region, highlighting the need for the revitalization of viticulture.

Keywords: Yozgat, Viticulture, Survey, Producer, Agricultural Activities

YOZGAT İLİ BAHADIN/SORGUN BELDESİNDE SÜRDÜRÜLEBILIR BAĞCILIK VE YEREL KALKINMA: BIR ANKET ÇALIŞMASI

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Özet

Bu araştırma, Yozgat ili Sorgun İlçesine bağlı Bahadın beldesinin bağcılık potansiyelini belirlemek amacıyla yürütülen bir anket çalışması olarak gerçekleştirilmiştir. Toplam 37 sorudan oluşan anket çalışması kapsamında 30 üretici ile yüz yüze görüşmeler gerçekleştirilmiştir. Anket soruları üreticilerin demografik yapısı, bağ alanı, işletme yapıları, bağ yetiştirme teknikleri ve kültürel uygulamalar, verim, pazarlama, ekonomik algı ve destekleri belirlemeye yönelik olarak hazırlanmıştır.

Ankette yer alan üreticilerin %46,43'ü kadın, %53,57'si erkek üreticiden oluşmaktadır. Kadın üreticilerin büyük çoğunluğu 50 yaş ve üzeri (%17,86), erkek üreticilerin de büyük çoğunluğu 50 yaş üzeri kişilerden oluşmaktadır. Kadınların %28,57'si mevcut bir bağlarının olduğunu ancak gerekli teknik ve kültürel işlemleri yerine getiremedikleri için verimden düştüğünü belirtmişlerdir. Ankete katılan 40 yaş ve üzeri kadınların tümü yeni bir bağ tesis etmek için istekli olduklarını da belirtmişlerdir. Ankete katılım sağlayan 40 yaş ve üzeri tüm erkek üreticiler de 10 da ve üzerinde bağ arazisinin olduğunu, aynı zamanda yeni bağ tesis etmek için istekli olduklarını dile getirmişlerdir. Ankete katılan tüm üreticiler bağcılığın farklı işleme tekniklerine de uygun olması nedeni ile karlı bir tarımsal üretim şekli olduğunu ancak bu konudaki teknik bilgi yetersizlikleri nedeni ile bu karlılığı elde edemediklerini belirtmişlerdir. Bağcılık alanında dikim, budama ve terbiye, sulama, hastalık ve zararlılarla mücadele ile gübreleme konularında bilgi eksiklikleri olduğunun bilincinde olan bu kişiler, yeni bilgileri almaya ve pratiğe aktarmaya da elverişli kişiler olarak belirlenmiştir.

Anket çalışması sonucunda üreticiler hem standart çeşitlerle yeni modern bağların tesis edilmesinin, hem de bölgede kaybolmaya yüz tutmuş geleneksel çeşitlerin korunarak muhafaza edilmesinin önemli olduğunu, bağcılığın canlandırılmasına ihtiyaç duyduklarını vurgulamışlardır.

Anahtar Kelimeler: Yozgat, Bağcılık, Anket, Üretici, Tarımsal Faaliyet

1. Giriş

Sorgun Türkiye'nin İç Anadolu Bölgesinde yer alan Yozgat iline ait bir ilçedir. Sorgun ilçesi, Yozgat'ın ilçelerinden batıda Merkez, güneyde Sarıkaya, doğuda Akdağmadeni ve Saraykent, kuzeydoğuda Çekerek ve kuzeyde Aydıncık ilçeleriyle birlikte kuzeybatıda da Çorum'un Alaca ilçesiyle komşudur (Anonim, 2026a). Bahadın, Yozgat ilinin Sorgun ilçesine bağlı bir beldedir. Bahadın beldesi Sorgun ilçe merkezine 21 km Yozgat il merkezine 56 km uzaklıkta, Sorgun-Akdağmadeni yol güzergahının 5 km güney batısında bulunmaktadır. Ankara Sivas Karayoluna 5 km Kayseri Samsun karayoluna ise 8 km uzaklıkta olup bu yönüyle pek çok güzergahın geçiş noktası üzerinde yer almaktadır (Köse et al., 2022). Hafif engebeli bir arazi yapısı üzerinde kurulan Bahadın'ın, tarihi Alişar höyüğüne 8 km uzaklıkta bulunması nedeniyle eski bir yerleşim yeri üzerine kurulu bir şehir olduğu da yapılan kazılardan ortaya çıkmıştır (Anonim, 2026 b).

Yazların sıcak ve kurak kışların soğuk ve sert geçtiği bölgenin yağışlı mevsimi ilkbahar ve sonbahardır. Bahadın'ın öncelikli geçim kaynağı tarım, özellikle tarla tarımıdır. Bununla birlikte Bahadın, eski bağların bulunduğu bir bölge olarak dikkati çekmektedir. Bölgede yapılan survey çalışmalarında bir zamanlar ciddi anlamda bir bağ varlığına sahip olduğu anlaşılmış olup, bu nedenle ciddi bir asma gen potansiyeline de sahiptir. Ancak günümüzde neredeyse tümünün aşısız fidanlarla oluşturulduğu bu bağların sulama, gübreleme ve hastalık ve zararlılarla mücadele gibi işlemlerin yapılmaması nedeni ile verimsizleştiği anlaşılmıştır. Eski bir bağcılık kültürünün bulunması, iklim bakımından da bağcılığa son derece uygun olması nedeniyle bölgenin bağcılığı konusunda çalışmalar yapılması önemlidir.

Bölgede istihdam imkanlarının sınırlı olması, buna karşın tarımla uğraşan genç nüfusun diğer beldelere kıyasla nispeten daha fazla olması bağcılığın canlandırılabilme ve sürdürülebilir olma potansiyelini de artırmaktadır. Kırsal dezavantajlı bu bölgede tarımın verimliliğinin artırılmasına yönelik yapılan anket çalışması bağcılığın gelişmesine destek sağlama bakımından önemlidir.

2. Materyal ve Yöntem

Bu çalışmanın materyalini Yozgat yöresi Bahadın beldesinde faaliyet gösteren tarımsal üreticilerle gerçekleştirilen bağcılık potansiyelini belirlemek adına yapılan anket çalışmasından elde edilen veriler oluşturmaktadır. Çalışma kapsamında Bahadın beldesinde bağcılık potansiyelini belirlemek üzere 30 üretici ile yüz yüze görüşmeler gerçekleşmiştir. Araştırma da yer alan anket formu 37 sorudan oluşmaktadır. Anket soruları üreticilerin demografik özellikleri,

işletme yapıları, bağ alanları ve üretim yapısı, fidan ve tesis özellikleri, yetiştirme teknikleri, bitki besleme ve toprak yönetimi, bitki koruma, budama ve bakım uygulamaları, pazarlama ve ürün değerlendirme, ekonomik algı ve tarımsal destekleri belirlemeye yönelik olarak hazırlanmıştır. Ayrıca anket çalışmasında bağcılık potansiyelinde gençlerin ve kadınların rolüne ilişkin sorular da yer almıştır.

Bölge halkının gelir düzeyi, yaşam kalitesi ve refah seviyesi, gıda güvenliğinin sürdürülebilirliği, ürün çeşitliliği, tarım alanlarının ve su kaynaklarının kullanımı, gübreleme programları gibi faktörlerin mevcut durumu ve bu alanda yapılabilecek uygulamaların belirlenmesi bakımından bu çalışma önem taşımaktadır.

3. Bulgular ve Tartışma

Anket çalışması sonucu, Bahadın beldesinde tarımsal üretimle ilgilenen üreticilerin profili genel olarak değerlendirildiğinde, genç nüfusunun nispeten daha fazla, yeniliklere açık, öğrenmeye hevesli kişilerden oluştuğu dikkati çekmektedir. Özelikle kadınların son derece aktif olduğu da bilinmektedir. Buradaki kadınların çok çeşitli sosyal aktiviteleri bulunan, farklı alanlarda açılan kurslara yüksek oranda katılım gösteren, verimli, aktif çalışan kadınlar olduğu belirlenmiştir. Ayrıca yapılan literatür çalışmalarında kadınların tarımsal üretimde aktif rol aldığına sıklıkla rastlanmaktadır (Lecoutere et al., 2023). Tablo 1' de anket çalışmasına katılan üreticilerin cinsiyet ve yaş profiline ilişkin yüzdelikler verilmiştir.

Tablo1: Anket çalışmasında üretici cinsiyet ve yaş profili

Kadın üretici (%46,43)	
30 yaş ve üzeri	*%3,57*
40 yaş ve üzeri	*%14,29*
50 yaş ve üzeri	*%17,86*
60 yaş ve üzeri	*%10,71*
Erkek üretici (53,57)	
20 yaş ve üzeri	*%3,57*
30 yaş ve üzeri	*%3,57*
40 yaş ve üzeri	*%10,71*
50 yaş ve üzeri	*%17,86*
60 yaş ve üzeri	*%17,86*

Ankete katılan üreticilerin %46,43 ü kadın, %53,57'si erkek üreticilerdir. Bu durum kadınların erkek üreticilere oranla tarımsal üretimlerde aldıkları roller sıkça rastladığımız bir tablo olarak vurgulanmaktadır (Lecoutere et al., 2023).

Bahadın bölgesinin üretici profili bakımından değerlendirme yapılırken kadın erkek cinsiyet eşitliği ön plana alınmıştır. Üzüm ve asma yapraklarının işleme tekniğine yönelik verilen cevaplarda gıda güvenliğini sağlamasına, kaliteli üzümlerden yüksek gelir elde etmesi bakımından profesyonel eğitimlerle bölge üreticisinin bu konuda bilinçlendirilmesi sonucuna varılmıştır. Kadın üreticilerin büyük çoğunluğu 50 yaş ve üzeri (%17,86), erkek üreticilerin de büyük çoğunluğu 50 yaş üzeri kişilerden oluşmaktadır.

Kadınların %28,57 si mevcut bir bağlarının olduğunu ancak gerektiği gibi bakılamadığı için verimden düştüğü belirtilmiştir. Ankete katılan 40 yaş ve üzeri kadınların tümü yeni bir bağ tesis etmek için istekli olduklarını da belirtmişlerdir. Ankete katılan 20 yaş ve üzeri ile 30 yaş ve üzeri erkek üreticilerden her iki grupta da %3,57'si bağlarının 2,5 da ve üzeri olduğunu belirtmiştir. 40 yaş ve üzeri üreticilerin ise bağ arazilerinin daha geniş olduğu dikkati çekmektedir. Ankete katılım sağlayan 40 yaş ve üzeri tüm erkek üreticiler de 10 da ve üzerinde bağ arazisinin olduğunu, aynı zamanda yeni bağ tesis etmek için istekli olduklarını vurgulamışlardır.

Bölge üreticisi hem kendi çeşitlerini koruyarak mevcut bağlarını bakımlı hale getirmek hem de yeni çeşitlerin bölgeye uyumlarını görmek için bağcılık eğitimini almak istemektedirler. Ankete katılan tüm üreticiler bağcılığın farklı işleme tekniklerine de uygun olması nedeni ile karlı bir tarımsal üretim şekli olduğunu ancak bu konudaki teknik bilgi yetersizlikleri nedeni ile gerektiği şekilde değerlendirilemediklerini belirtmişlerdir. Bağcılık alanında dikim, budama ve terbiye, sulama, hastalık ve zararlılarla mücadele ile gübreleme konularında bilgi eksiklikleri olduğunun bilincinde olan bu kişiler, yeni bilgileri almaya ve pratiğe aktarmaya da elverişli kişilerdir.

4. Sonuç

Bu çalışma kapsamında Yozgat Bahadın beldesinde bağcılık alanında faaliyet gösteren üreticilerin karşılaştıkları sosyal, ekonomik ve yapısal sorunlar anket yöntemi kullanılarak belirlenmiştir. Anket sonuçları kapsamında Bahadın beldesinde bağların büyük bir kısmının

geleneksel yöntemlerle kurulduğu, çoğunlukla aşısız, kendi kökleri üzerinde yetişmiş asmalar olduğu anlaşılmaktadır. Filoksera başta olmak üzere bağ kanseri özellikle eski bağlarda çok yaygın olup, bu bağlarda neredeyse hiç verim alınamamaktadır. Ayrıca eski bağlardaki çeşitlerin büyük bir kısmının düşük verimli çeşitlerden oluşması bağcılıkta kalite ve verimliliğin artırılmasına yönelik modern ve sürdürülebilir tekniklerin kullanımının yaygınlaştırılmasını zorunlu kılmaktadır. Üreticilerin anket sonuçlarında da belirttikleri gibi bağcılık, bağlardan alınan verimin artırılması durumda son derece karlı bir üretim şeklidir. Bu nedenle modern bağcılık teknikleri ile verimliliğin artırılması için gerekli eğitimlerin verilmesi, çeşit x anaç kombinasyonu, kış ve yaz budamaları, terbiye şekli, hastalık ve zararlılarla mücadele, sulama ve gübreleme programlarının üreticilere bilgilendirilmesi gerekmektedir.

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INSECTİCİDAL POTENTİAL OF CANNABİS SATİVA L. AGAİNST PEST INSECTS

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Abstract

The intensive and indiscriminate use of synthetic insecticides has led to significant problems, including the development of resistance in pest insects, environmental pollution, and adverse effects on human health. This situation has increased the need for environmentally friendly and sustainable alternative control methods, bringing studies on the use of plant-based insecticides to the forefront. Generally, plant-based insecticides are relatively inexpensive, easy to apply, and in some cases effective even at low doses. Furthermore, due to their multiple modes of action, these products may delay the development of resistance in pest insects. In recent years*, C. sativa* L., one of the plants with high biological activity potential, has attracted considerable attention due to its richness in cannabinoids, monoterpenes, sesquiterpenes, and phenolic compounds, and has been considered a potential source of biopesticides for pest management. Various studies have investigated the insecticidal activity of *C. sativa*. Research findings have demonstrated that *C. sativa* can exhibit toxic, repellent, and growth-regulating effects on insects through different mechanisms of action. It is believed that the high levels of terpenoid and flavonoid compounds present in the plant contribute to its insecticidal properties. Studies reported in the literature have shown that *C. sativa* exhibits insecticidal activity against many economically important pest species, including *Tetranychus urticae*, *Oryzaephilus surinamensis, Tribolium confusum, Trogoderma granarium, Sitophilus oryzae, Aedes aegypti, Aphis craccivora*, and *Myzus persicae.* This study aims to compile the existing literature on pest species against which *C. sativa* demonstrates insecticidal activity and to evaluate the biopesticide potential of this plant.

Keywords: Cannabis sativa, plant-based insecticides, biopesticides

CANNABIS SATIVA L. BİTKİSİNİN ZARARLI BÖCEKLERE KARŞI İNSEKTİSİDAL POTANSIYELİ

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Özet

Sentetik insektisitlerin yoğun ve bilinçsiz kullanımı sonucunda zararlı böceklerde direnç gelişimi, çevresel kirlilik ve insan sağlığına yönelik olumsuz etkiler gibi önemli sorunlar ortaya çıkmıştır. Bu durum, çevre dostu ve sürdürülebilir alternatif mücadele yöntemlerine olan ihtiyacı artırmış ve bitkisel kökenli insektisitlerin kullanımına yönelik çalışmaları ön plana çıkarmıştır. Genel olarak bitkisel insektisitler nispeten ucuz, kolay uygulanabilir ve bazı durumlarda düşük dozlarda dahi etkili olabilmektedir. Ayrıca bu ürünler, birden fazla etki mekanizmasına sahip olmaları nedeniyle zararlı böceklerde direnç gelişimini geciktirebilmektedir. Son yıllarda biyolojik aktivite potansiyeli yüksek bitkiler arasında yer alan *C. sativa* L., içerdiği kannabinoidler, monoterpen ve seskiterpen bileşikleri ile fenolik maddeler bakımından zengin olması nedeniyle dikkat çekmekte ve zararlı böceklerle mücadelede potansiyel bir biyopestisit kaynağı olarak değerlendirilmektedir. *Cannabis sativa*'nın insektisidal etkinliğini inceleyen farklı çalışmalar bulunmaktadır. Yapılan araştırmalar sonucunda, *C. sativa*'nın böcekler üzerinde farklı etki mekanizmaları yoluyla toksik, repellent ve gelişim düzenleyici etkiler gösterebildiği bildirilmektedir. Bitkinin içeriğinde bulunan yüksek düzeyde terpenoid ve flavonoid bileşiklerinin, *C. sativa*'ya insektisit özelliği kazandırdığı düşünülmektedir. Literatürde yer alan çalışmalar, *C. sativa*'nın *Tetranychus urticae, Oryzaephilus surinamensis, Tribolium confusum, Trogoderma granarium, Sitophilus oryzae, Aedes aegypti, Aphis craccivora* ve *Myzus persicae* gibi birçok ekonomik öneme sahip zararlı tür üzerinde insektisidal etkinlik gösterebildiğini ortaya koymaktadır. Bu çalışma ile *C. sativa*'nın insektisidal etki gösterdiği zararlı türlere ilişkin mevcut literatürün derlenmesi ve bitkinin biyopestisit potansiyelinin değerlendirilmesi amaçlanmıştır.

Anahtar Kelimeler: *Cannabis sativa*, bitkisel insektisitler, biyopestisitler

1. Introduction

One of the most important factors threatening agricultural productivity and quality is insect pests. Arthropod pests are reported to cause approximately 18–26% annual crop losses in agricultural production worldwide (McPartland & Sheikh, 2018). A significant portion of these losses occurs under field conditions, while the remaining losses arise during storage. In addition to the economic losses caused by insect pests, diseases transmitted by vector insects pose serious risks to human and animal health (McPartland & Sheikh, 2018). Since the mid-twentieth century, the widespread use of synthetic insecticides has provided important advantages in pest control; however, the intensive and improper use of these chemicals has resulted in serious environmental and ecological problems. The persistence of synthetic pesticides in soil, water, and air, their harmful effects on beneficial organisms, and their toxic impacts on human health have become major concerns (Ona et al., 2021). Furthermore, resistance development against pesticides has been observed in many pest species, making the development of alternative pest management strategies essential (Mazzara et al., 2023).

In this context, botanical pesticides have become an important research area in sustainable pest management in recent years. Botanical insecticides are reported to delay resistance development in pests due to their low residue levels, lower environmental impact, and multiple mechanisms of action (Ona et al., 2021). In particular, essential oils are considered an important component of plant defense systems and may exhibit toxic, repellent, and growth-regulating effects against many pest species (Benelli et al., 2018). One of the remarkable species among botanical insecticides is Cannabis sativa L. This plant contains more than 500 chemical compounds, among which phytocannabinoids, terpenoids, and flavonoids are particularly important (Ona et al., 2021). Volatile compounds such as monoterpenes and sesquiterpenes are known to exhibit repellent and toxic effects against insect pests (McPartland & Sheikh, 2018). The use of Cannabis sativa against pests is not limited to modern research. Historical records indicate that the leaves and branches of this plant were placed around beds to repel mosquitoes and bed bugs (Ona et al., 2021). In addition, there is evidence that dried plant material was powdered and used in traditional pest control practices (Ona et al., 2021).

Recent experimental studies have demonstrated that essential oils obtained from Cannabis sativa exhibit significant biological activity against various pest species. For example, essential oils derived from industrial hemp have been reported to exert toxic effects against economically important pests such as Myzus persicae, Musca domestica, and Spodoptera littoralis (Benelli et al., 2018). Furthermore, essential oils formulated as nanoemulsions were shown to be effective against mosquito larvae and significantly reduce population development (Mazzara et al., 2023).

Studies conducted on stored-product pests also indicate that Cannabis sativa extracts possess significant potential. For instance, ethanolic extracts were reported to exhibit repellent effects against Plodia interpunctella larvae and significantly reduce larval development and fecundity (Prvulović et al., 2023). These findings suggest that Cannabis sativa may be used as an alternative biopesticide in the management of stored-product pests.

Currently, a considerable portion of studies aimed at increasing the efficacy of botanical insecticides focuses on formulation technologies. Due to disadvantages such as high volatility and low stability of essential oils, the development of micro- and nanoemulsion systems has been recommended. These systems enhance the stability of active compounds, strengthen biological efficacy, and may increase toxicity against target organisms (Mazzara et al., 2023).

In light of all this information, Cannabis sativa L. is considered a potential source of biopesticides against insect pests due to its rich chemical composition and broad spectrum of biological activity. The aim of this study is to comprehensively evaluate the insecticidal potential of *C. sativa* L., focusing on its chemical composition, mechanisms of action, and efficacy against different pest groups.

2. Chemical Composition and Biologically Active Compounds of *Cannabis sativa*

Cannabis sativa L. is one of the most remarkable plants in terms of biological activity due to its rich secondary metabolite profile. The chemical composition of this plant consists of phytocannabinoids, terpenoids, flavonoids, phenolic compounds, and other secondary metabolites, many of which function as part of the plant's defense mechanism against pests (Ona et al., 2021).

More than 500 chemical compounds have been identified in *C. sativa*, a significant proportion of which are biologically active secondary metabolites. In particular, volatile compounds such as phytocannabinoids, monoterpenes, and sesquiterpenes exhibit toxic, repellent, and antifeedant effects against insect pests (Ona et al., 2021; McPartland & Sheikh, 2018).

2.1. Phytocannabinoids

Phytocannabinoids are among the most important chemical compound groups specific to Cannabis sativa. The best-known compounds in this group are Δ9-tetrahydrocannabinol (THC) and cannabidiol (CBD). These compounds are synthesized in the plant not directly but as precursor molecules, tetrahydrocannabinolic acid (THCA) and cannabidiolic acid (CBDA) (McPartland & Sheikh, 2018). Although the effects of phytocannabinoids on pests are not yet fully understood, these compounds have been reported to exert toxic effects on certain insect species and inhibit feeding behavior. In particular, THC may exhibit direct toxic effects on some insect species, whereas terpenoid compounds are believed to play the primary role in repellent activity (McPartland & Sheikh, 2018).

In addition, other phytocannabinoids found in Cannabis sativa include compounds such as cannabichromene (CBC), cannabigerol (CBG), and cannabinol (CBN), which are thought to enhance biological activity through synergistic interactions (Ona et al., 2021).

2.2. Terpenoids and Essential Oil Compounds

Terpenoids are among the most important compound groups contributing to the insecticidal potential of Cannabis sativa. The essential oil fraction of the plant mainly consists of monoterpene and sesquiterpene hydrocarbons (Benelli et al., 2018).

The major terpenoids commonly found in Cannabis sativa essential oils include: α-pinene, β-myrcene, limonene, linalool, (E)-caryophyllene, terpinolene. These compounds are reported to affect the insect nervous system and may exhibit repellent, fumigant, or contact toxicity (McPartland & Sheikh, 2018; Benelli et al., 2018). For example, chemical analysis of the essential oil obtained from the Felina 32 cultivar revealed that (E)-caryophyllene (45.4%), myrcene (25.0%), and α-pinene (17.9%) were dominant compounds. The high abundance of these compounds is considered one of the main factors increasing the biological activity of the essential oil against insects (Benelli et al., 2018). It has also been reported that the insecticidal

effects of terpenoids are not limited to chemical toxicity, but may additionally alter insect behavior by affecting feeding and oviposition activities (McPartland & Sheikh, 2018).

2.3. Flavonoids and Phenolic Compounds

Cannabis sativa is also rich in flavonoids and phenolic compounds. Reported flavonoids include: quercetin, kaempferol, apigenin, orientin, cannflavin A and B (McPartland & Sheikh, 2018). Rather than direct insecticidal activity, phenolic compounds and flavonoids generally exhibit indirect biological effects such as antifeedant activity, growth inhibition, and oviposition suppression. These compounds are also thought to enhance overall biological activity through synergistic interactions with other secondary metabolites (Ona et al., 2021).

2.4. Glandular Trichomes and Secondary Metabolite Production

In Cannabis sativa, the production of secondary metabolites occurs largely through glandular trichomes. It has been reported that two main types of glandular trichomes are present on the plant: sessile glandular trichomes and stalked glandular trichomes. Sessile trichomes are distributed across the entire plant surface, whereas stalked trichomes are concentrated particularly on female flowers (McPartland & Sheikh, 2018). The resinous secretion produced by these trichomes provides both physical and chemical defense mechanisms against insects. The sticky resin secreted from trichomes may restrict the movement of small insects, causing mechanical mortality, while simultaneously enhancing the effects of chemical compounds (McPartland & Sheikh, 2018). Furthermore, observations have shown that some aphid species lose mobility and die shortly after contacting glandular trichomes. This demonstrates that the natural defense mechanism of Cannabis sativa relies not only on chemical but also on physical factors (McPartland & Sheikh, 2018).

2.5. Variations in Chemical Composition

The chemical composition of Cannabis sativa may vary depending on numerous factors such as genetic background, cultivation conditions, harvest time, plant part used, and extraction method (Ona et al., 2021). For example, significant chemical differences exist among different chemovars and cultivars, making comparisons of biological activity difficult. Therefore, it has been emphasized that insecticidal studies should be conducted using standardized plant material (Ona et al., 2021).

3. Mechanisms of Action of Cannabis sativa Against Insect Pests

The efficacy of botanical insecticides generally results from the combined effects of multiple biological mechanisms. The effects of Cannabis sativa L. against insect pests occur through several mechanisms, including nervous system disruption, feeding inhibition, repellent activity, developmental suppression, and oviposition deterrence. These mechanisms are primarily associated with the biochemical activities of terpenoids, phytocannabinoids, and phenolic compounds present in the plant (McPartland & Sheikh, 2018; Ona et al., 2021).

3.1. Effects on the Nervous System

A significant portion of the insecticidal activity of Cannabis sativa essential oils is associated with their toxic effects on the insect nervous system. Terpenoid compounds are

reported to exert neurotoxic effects by disrupting synaptic transmission, leading to physiological disorders that ultimately result in mortality (McPartland & Sheikh, 2018).

In particular, monoterpenes are known to disrupt the normal functioning of nerve cells in insects, causing loss of motor coordination, paralysis, and death. These compounds may interfere with the functioning of ion channels, thereby blocking nerve impulse transmission (Ona et al., 2021).

In a study conducted by Benelli et al. (2018), Cannabis sativa essential oils were reported to produce toxic effects against various pest species, and this activity was associated particularly with the effects of essential oil constituents on the nervous system.

3.2. Acetylcholinesterase (AChE) Inhibition

One of the important mechanisms of action of botanical insecticides is the inhibition of the acetylcholinesterase (AChE) enzyme. This enzyme regulates nerve transmission by breaking down acetylcholine within the nervous system. Inhibition of AChE leads to acetylcholine accumulation, resulting in continuous nerve stimulation, muscle spasms, paralysis, and eventually death. Some terpenoid compounds present in Cannabis sativa essential oils have been reported to suppress AChE activity, and this mechanism may contribute to insecticidal efficacy (Ona et al., 2021).

The effects of terpenoid compounds on this enzyme may occur through mechanisms similar to those of synthetic organophosphate and carbamate insecticides, but generally with lower environmental residues and reduced toxicity.

3.3. Repellent Activity

Repellent activity is one of the most important biological effects of Cannabis sativa against pests. The characteristic odor produced by essential oil components prevents insect pests from approaching the plant, thereby strengthening its natural defense system. Historical records indicate that Cannabis sativa was used as a repellent against mosquitoes and other hematophagous insects. The use of plant branches or leaves in living areas was reported to repel pests (Ona et al., 2021). Experimental studies have also shown that Cannabis sativa extracts produce moderate repellent effects against certain pest species. For example, studies on Plodia interpunctella larvae demonstrated that extracts at specific concentrations exhibited repellent activity against larvae (Prvulović et al., 2023).

3.4. Antifeedant Activity

Another important effect of Cannabis sativa compounds is the suppression of insect feeding behavior. Antifeedant activity plays an important role in reducing plant damage by preventing pests from consuming plant tissues. Terpenoids and phenolic compounds may affect insect taste receptors, thereby reducing feeding activity and causing developmental retardation (McPartland & Sheikh, 2018). This effect is reported to be particularly pronounced during larval stages, and long-term feeding inhibition may slow larval development and reduce population growth.

3.5. Oviposition Deterrence

Cannabis sativa extracts are known to suppress oviposition behavior in certain insect species. Oviposition deterrence plays an important role in controlling population development. Chemical signals produced by plant essential oils may negatively affect oviposition site selection by female insects. This results in reduced egg laying and consequently lower population density (Mazzara et al., 2023). In a study conducted by Mazzara et al. (2023), Cannabis sativa essential oil and its nanoemulsion formulation significantly reduced fertility rates in mosquitoes and limited population growth.

3.6. Effects on Development and Life Cycle

Cannabis sativa extracts are known to exert significant effects on the developmental processes of insect pests. These effects include prolonged larval development duration, reduced pupation rate, decreased adult emergence, and reduced fertility and fecundity. For example, studies conducted on Plodia interpunctella demonstrated that Cannabis sativa extracts prolonged larval development and reduced egg production capacity (Prvulović et al., 2023). Similarly, even sublethal doses of Cannabis sativa essential oils have been reported to negatively affect the life cycle of insect pests and thereby limit population growth (Mazzara et al., 2023).

3.7. Physical Defense Mechanisms

The defense of Cannabis sativa against pests is not limited to chemical mechanisms alone. The resinous substances secreted by glandular trichomes located on the plant surface may physically inhibit the movement of small insects. This resinous structure causes insect pests to adhere to the plant surface, and loss of mobility may ultimately result in death. This demonstrates that the natural defense system of Cannabis sativa consists of both physical and chemical components (McPartland & Sheikh, 2018).

4. Insecticidal Effects of Cannabis sativa Against Different Pest Groups

Studies investigating the insecticidal potential of extracts and essential oils obtained from Cannabis sativa L. demonstrate that this plant is effective against numerous pest species belonging to different insect orders. The available literature reports significant biological activity particularly against Diptera, Hemiptera, Lepidoptera, and stored-product pests. These effects are generally attributed to the synergistic activity of essential oil constituents and phytocannabinoids (Wanas et al., 2020; Satyal & Setzer, 2015).

4.1. Mosquitoes (Diptera: Culicidae)

Mosquitoes are among the most important vector organisms affecting human health, and the development of alternative biopesticides has intensified research on this pest group. One of the earliest experimental studies investigating the insecticidal effects of *C. sativa* against mosquitoes was conducted by Jalees et al. (1993), who reported that plant extracts caused mortality in mosquito larvae. Later, Thomas et al. (2000) demonstrated that Cannabis sativa essential oil exhibited significant insecticidal activity against mosquito larvae, and this effect was mainly associated with volatile constituents. Similarly, Maurya et al. (2008) reported that Cannabis sativa extracts caused high mortality in *Culex quinquefasciatus* larvae and possessed considerable larvicidal potential. Recent studies have shown that *Cannabis sativa* essential oils not only induce larval mortality but also affect population development. For example, Bedini et al. (2016) reported that *C. sativa* essential oil was effective against *Aedes albopictus* and

could be used as an alternative biopesticide for the control of this species. Furthermore, Rossi et al. (2020) demonstrated that nanoemulsion formulations of *C. sativa* essential oils exhibited high insecticidal activity against mosquito larvae. These findings indicate that *C. sativa* is an important candidate biopesticide for mosquito control.

4.2. Aphids (Hemiptera: Aphididae)

Aphids are important pest groups that feed on plant sap and play a major role in the transmission of plant viruses. Studies investigating the effects of Cannabis sativa essential oils on aphids have revealed significant aphicidal activity. In particular, Górski et al. (2009) reported that Cannabis sativa essential oil was effective against Dysaphis plantaginea and significantly reduced population density. Similarly, Górski et al. (2016) demonstrated that Cannabis sativa essential oil caused mortality in Aulacorthum solani and Tetranychus urticae. These studies indicate that Cannabis sativa essential oils are particularly effective against piercing-sucking pests and may be incorporated into plant protection programs.

4.3. Lepidopteran Pests

Pests belonging to the order Lepidoptera cause serious economic losses by feeding on plant tissues, particularly during their larval stages. In a study conducted by Park et al. (2019), cannabidiol (CBD) obtained from *C. sativa* affected the feeding behavior of *Manduca sexta* larvae and exhibited insecticidal activity.

In addition, Yadav and Patel (2017) reported that botanical extracts produced toxic effects against *Spodoptera litura* larvae and slowed their developmental process. These findings suggest that *C. sativa* components may suppress the development of Lepidopteran larvae.

4.4. Stored-Product Pests

Stored-product pests pose serious risks to food security, and the development of alternative control methods against these pests is of great importance. In a study conducted by Mantzoukas et al. (2020), cannabidiol (CBD) oil exhibited high insecticidal activity against stored-product pests such as *Tribolium confusum, Oryzaephilus surinamensis*, and *Plodia interpunctella*. Particularly at high doses, 100% mortality was reported. Furthermore, the same study demonstrated that the applied extracts shortened the lifespan of pests and significantly reduced progeny production. These results suggest that *C. sativa* may serve as an alternative biopesticide in the management of stored-product pests.

4.5. Mites and Other Pests

The effects of *C. sativa* extracts on mites and other arthropod pests have also been investigated. For example, Tabari et al. (2020) reported that *C. sativa* essential oil exhibited significant acaricidal activity against *Dermanyssus gallinae* and *Hyalomma dromedarii*. Similarly, Nasreen et al. (2020) found that *C. sativa* extracts were effective against *Rhipicephalus microplus* ticks. These studies demonstrate that *C. sativa* exhibits biological activity not only against insects but also against mites and ticks.

6. Conclusion and Future Perspectives

Cannabis sativa has attracted considerable attention as a potential biopesticide candidate in pest management due to its rich phytochemical composition. The essential oils and extracts of this plant are rich in biologically active compounds such as terpenoids, phytocannabinoids, and flavonoids, which are known to affect the insect nervous system, feeding behavior, and developmental processes (McPartland & Sheikh, 2018; Ona et al., 2021).

Studies available in the literature demonstrate that *C. sativa* extracts exhibit insecticidal, repellent, and growth-suppressive effects against different pest groups. In particular, research conducted on mosquitoes, aphids, Lepidopteran larvae, and stored-product pests indicates that this plant possesses broad-spectrum biological activity (Bedini et al., 2016; Maurya et al., 2008; Mantzoukas et al., 2020; Rossi et al., 2020). Furthermore, several studies have reported that Cannabis sativa-based products are also effective against mites and other arthropod pests (Tabari et al., 2020).

The insecticidal efficacy of *C. sativa* is mainly associated with the neurotoxic effects of essential oil constituents on the insect nervous system and their ability to suppress feeding behavior. These compounds are thought to act through mechanisms such as acetylcholinesterase inhibition, disruption of ion channel function, and interference with metabolic processes that slow larval development (Satyal & Setzer, 2015; Park et al., 2019). In addition, several studies have shown that compounds derived from this plant may exert sublethal effects, prolong insect developmental duration, and reduce fecundity values (Mantzoukas et al., 2020).

In recent years, increasing attention has been directed toward the use of nanoformulation technologies to enhance the efficacy of *C. sativa* essential oils. Nanoemulsion formulations have been reported to improve the stability of essential oils, provide controlled release, and enhance insecticidal activity (Rossi et al., 2020; Mazzara et al., 2023). These developments are considered an important step toward transforming Cannabis sativa-based products into commercial biopesticides.

Nevertheless, there remain several important research gaps regarding the use of Cannabis sativa in pest management. First, a significant proportion of current studies have been conducted under laboratory conditions, whereas field studies remain limited. Determining efficacy, persistence, and environmental interactions under field conditions is crucial for evaluating the practical application potential of this plant (Ona et al., 2021). Moreover, the effects of Cannabis sativa-based products on non-target organisms should be investigated in detail. In particular, evaluating their impacts on beneficial insects, natural enemies, and soil organisms is considered essential for environmental sustainability (Benelli et al., 2018; Mazzara et al., 2023).

Future studies should also evaluate combinations of Cannabis sativa essential oils with other plant extracts in order to identify synergistic effects. Furthermore, comparisons among different chemotypes and the isolation of active compounds may contribute to optimizing insecticidal efficacy. In addition, the development of controlled-release systems, microencapsulation techniques, and nanoformulation technologies may accelerate the commercial application of these plant-based products (Rossi et al., 2020).

In conclusion, current literature indicates that *C. sativa* may represent an important source of biopesticides for pest management. However, to fully reveal this potential, detailed biological activity studies against different pest species, improvements in formulation

technologies, and field-based evaluations are required. Expanding such studies will contribute significantly to the development of sustainable agricultural practices and the reduction of synthetic pesticide use.

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PLANT-BASED INSECTİCİDES İN STORED-PRODUCT PEST MANAGEMENT: CURRENT APPROACHES AND FUTURE PROSPECTS

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Abstract

Stored products are highly important worldwide for food security and economic sustainability. However, insect pests that infest products during storage cause significant losses in both quantity and quality. Species such as *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae), and *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) are among the most common and economically significant pests of stored products. Synthetic insecticides have been widely used for many years to control these pests; however, such practices have led to major problems, including the development of pest resistance, environmental pollution, and residue in food products. In recent years, plant-based insecticides have attracted attention as environmentally friendly and sustainable alternatives. Plant essential oils and extracts have shown various biological activities against stored-product pests, including contact toxicity, fumigant effects, repellent activity, and oviposition deterrence. In particular, essential oils from plants in the families Lamiaceae, Apiaceae, and Asteraceae have been reported in many studies to have high potential for controlling stored-product pests. The effects of these natural compounds are thought to occur through different mechanisms, such as impacts on the nervous system, inhibition of acetylcholinesterase, and behavioural changes. This review discusses the potential use of plant-based insecticides in managing stored-product pests, based on current literature. It comprehensively evaluates the effects of plant essential oils and extracts on various stored-product pest species, their mechanisms of action, advantages, and limitations. In addition, it addresses new-generation approaches such as nanoformulations and controlled-release systems, and discusses future prospects for the use of plant-based insecticides. The study highlights that plant-based insecticides may represent an important alternative for the sustainable management of stored-product pests.

Keywords: Stored-product pests; Botanical insecticides; Essential oils; Biopesticides; Sustainable pest management

DEPOLANMIŞ ÜRÜN ZARARLILARINDA BITKISEL KÖKENLI İNSEKTISITLERIN KULLANIM POTANSIYELI: GÜNCEL YAKLAŞIMLAR

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Özet

Depolanmış ürünler, dünya genelinde gıda güvenliği ve ekonomik sürdürülebilirlik açısından büyük öneme sahiptir. Ancak depolama sürecinde ortaya çıkan zararlı böcekler, ürün miktarında ve kalitesinde önemli kayıplara neden olmaktadır. *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae) ve *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) gibi türler, depolanmış ürünlerde en yaygın ve ekonomik açıdan önemli zararlılar arasında yer almaktadır. Bu zararlılarla mücadelede uzun yıllardır sentetik insektisitler yaygın olarak kullanılmakta, ancak bu uygulamalar zararlılarda direnç gelişimi, çevresel kirlilik ve gıda ürünlerinde kalıntı sorunları gibi önemli problemlere yol açmaktadır. Son yıllarda, bitkisel kökenli insektisitler çevre dostu ve sürdürülebilir alternatifler olarak ön plana çıkmıştır. Bitki uçucu yağları ve ekstraktları, depo zararlıları üzerinde kontakt toksisite, fumigant etki, repellent etki ve ovipozisyonu engelleyici etkiler gibi çeşitli biyolojik aktiviteler göstermektedir. Özellikle Lamiaceae, Apiaceae ve Asteraceae familyalarına ait bitkilerden elde edilen uçucu yağların, depo zararlılarının kontrolünde yüksek potansiyele sahip olduğu birçok çalışmada bildirilmiştir. Bu doğal bileşiklerin etkilerinin, sinir sistemi üzerine etkiler, asetilkolinesteraz inhibisyonu ve davranışsal değişiklikler gibi farklı mekanizmalar aracılığıyla ortaya çıktığı düşünülmektedir. Bu derlemede, depolanmış ürün zararlılarının yönetiminde bitkisel kökenli insektisitlerin kullanım potansiyeli güncel literatür ışığında ele alınmıştır. Bitki uçucu yağları ve ekstraktlarının farklı depo zararlı türleri üzerindeki etkileri, etki mekanizmaları, avantajları ve sınırlılıkları kapsamlı şekilde değerlendirilmiştir. Ayrıca, nanoformülasyonlar ve kontrollü salınım sistemleri gibi yeni nesil yaklaşımlar da ele alınarak, bitkisel insektisitlerin gelecekteki kullanım olanakları tartışılmıştır. Bu çalışma, depo zararlılarının sürdürülebilir yönetimi için bitkisel kökenli insektisitlerin önemli bir alternatif oluşturabileceğini ortaya koymaktadır.

Anahtar Kelimeler: Depo zararlıları, bitkisel insektisitler, uçucu yağlar, biyopestisitler, sürdürülebilir mücadele

1. Introduction

The rapid increase in the world population has made the reduction of losses in food production and storage processes a critical global issue. It is estimated that the world population will reach approximately 9–10 billion by 2050, and current food production will need to increase by nearly 70%. This situation has made the reduction of post-harvest losses a fundamental strategy for ensuring food security (Bezabih et al., 2022). Stored-product pests are among the most important causes of post-harvest losses, leading to significant quantitative and qualitative losses in cereals, legumes, and processed food products. Losses caused by insect pests not only reduce product weight but also result in quality problems such as mold formation, increased acidity, odor deterioration, and microbial contamination. Furthermore, insect feces and exuviae contaminate products and reduce their commercial value (Mesterházy et al., 2020).

It has been reported that insect-related damage during storage can reach very high levels in some cases. For example, losses caused by insect infestation in stored products may reach up to 50–60% (Luo et al., 2020). In addition, storage losses exceeding 25% in cereal products have been reported in certain regions (Tadesse and Basedow, 2004). These losses are particularly higher in developing countries and pose significant risks in terms of food security and economic sustainability. Among stored-product pests, species belonging particularly to the orders Coleoptera and Lepidoptera are of major economic importance. Species such as *Sitophilus* spp., *Tribolium* spp., *Rhyzopertha dominica*, and *Oryzaephilus surinamensis* are among the most common pests found in stored products (Nayak and Daglish, 2018). These pests cause direct damage by consuming the embryo part of grains or create secondary damage by feeding on damaged kernels.

Synthetic insecticides have been widely used for many years in the control of stored-product pests. Although synthetic insecticides provide rapid and effective control, their excessive and improper use has resulted in various adverse effects. These negative impacts include resistance development in pests, environmental pollution, reduction in biodiversity, and toxic effects on human health (Kim et al., 2017). Moreover, some synthetic insecticides may accumulate in the food chain and cause serious long-term health problems (Sharma et al., 2019).

The problems caused by synthetic insecticides have increased interest in alternative pest management methods. Among these alternatives, plant-derived insecticides occupy an important place due to their environmentally friendly and sustainable characteristics. Plant-

derived insecticides are obtained from natural resources and present a lower risk of environmental residue because of their biodegradable properties. In addition, these compounds are reported to exhibit lower toxicity toward non-target organisms (Hasan et al., 2023).

The use of plant-derived insecticides is not a new approach and historically dates back to ancient times. Plant extracts were known to be used against insect pests in ancient China, India, and Egypt. In particular, records regarding the insecticidal use of the neem plant (*Azadirachta indica*) date back thousands of years (Isman, 2020). This historical use demonstrates that plant-derived insecticides are part of natural defense systems. Plants produce numerous secondary metabolites as defense mechanisms against pests. These metabolites include a wide variety of chemical compounds such as monoterpenes, sesquiterpenes, flavonoids, alkaloids, phenols, and tannins. These compounds can suppress pest populations by exhibiting toxic, repellent, antifeedant, or growth-regulating effects on pests (Isman, 2020; Rajendran and Sriranjini, 2008).

The effectiveness of plant-derived insecticides is associated with different biological activities such as fumigant, contact, and repellent effects. These compounds may affect the nervous system of pests, causing paralysis, inhibiting feeding behavior, or disrupting reproductive systems (Boate and Abalis, 2020). Furthermore, some plant-derived compounds have been reported to exhibit insect growth-regulating effects by interfering with developmental processes. In recent years, increasing interest in plant-derived insecticides has been largely associated with their high potential for use in Integrated Pest Management (IPM) programs. The combined use of plant products with hermetic storage, modified atmosphere applications, and biological control methods can provide more effective management of stored-product pests (Hasan et al., 2023).

Nevertheless, plant-derived insecticides also have certain limitations. The high volatility of essential oils, low water solubility, and sensitivity to environmental factors are among the major factors limiting their effectiveness (Ragaei and Sabry, 2014). To overcome these limitations, nanotechnology-based formulation systems have been developed in recent years. Nanotechnology is one of the most important technological approaches used to improve the stability, bioavailability, and controlled release of plant-derived insecticides. Nanoemulsion and microencapsulation systems enable active compounds to reach target surfaces more effectively in the form of small particles and provide prolonged biological activity (Pavoni et al., 2019; Benelli et al., 2020). In addition, nanocarrier systems help preserve the effectiveness

of plant-derived compounds during storage by increasing their resistance to environmental factors such as light, temperature, and oxygen (De Oliveira et al., 2014).

In recent years, novel extraction techniques developed to improve the efficacy of plant-derived insecticides have also attracted attention. Methods such as microwave-assisted extraction, ultrasound-assisted extraction, and supercritical fluid extraction increase the yield of active compounds obtained from plants, thereby facilitating their industrial-scale utilization. All these developments indicate that plant-derived insecticides may serve as an important alternative in the management of stored-product pests. However, for the commercial-scale use of these compounds, further studies are needed regarding standardization, formulation development, and efficacy testing under field conditions. In addition, issues such as the long-term effects of plant-derived insecticides, their impacts on non-target organisms, and their economic feasibility should also be investigated in detail (Isman, 2020).

The aim of this review is to comprehensively discuss the importance of plant-derived insecticides, their mechanisms of action, and the technological innovations developed in recent years for the management of stored-product pests, and to evaluate the current body of knowledge in light of recent literature.

2. Importance of Botanical Insecticides in Stored-Product Pests

The development of effective and sustainable methods for the control of stored-product pests is of great importance for ensuring global food security. Traditionally, synthetic insecticides have been widely used in the management of storage pests, providing rapid and effective results. However, the long-term and intensive use of these chemicals has resulted in serious problems such as resistance development in pest populations, environmental pollution, and adverse effects on human health (Kim et al., 2017; Sharma et al., 2019). Resistance development against synthetic insecticides is considered one of the most significant challenges in the control of stored-product pests. In particular, resistance to various insecticide groups has been reported in species such as Sitophilus oryzae, Tribolium castaneum, and Rhyzopertha dominica (Nayak and Daglish, 2018). The development of resistance reduces the effectiveness of applied insecticides and necessitates the use of higher doses. This situation increases both economic costs and environmental risks (Dayan et al., 2009). These problems have made the development of environmentally friendly and sustainable alternative pest management methods essential. Botanical insecticides have significant potential as alternatives to synthetic

insecticides due to their natural origin and biodegradable properties. Their short persistence in the environment, generally lower adverse effects on non-target organisms, and ability to delay resistance development are among their major advantages (Isman, 2020; Hasan et al., 2023).

The importance of botanical insecticides is noteworthy not only from an environmental perspective but also from an economic standpoint. Particularly in developing countries, the cost of synthetic insecticides can be high for small-scale producers. Therefore, the use of insecticides obtained from local plant species offers low-cost and accessible alternatives (Affognon et al., 2015). In addition, the production of botanical insecticides from local resources contributes to supporting rural economies and promoting sustainable agricultural practices. Another factor increasing the importance of botanical insecticides is their potential use in Integrated Pest Management (IPM) programs. IPM strategies are multifaceted approaches aiming to keep pest populations below the economic threshold while reducing dependence on chemical control. Botanical insecticides can provide more effective results when used together with biological control agents and physical control methods (Nikolaou et al., 2021). In particular, the repellent and fumigant effects of essential oils play an important role in controlling stored-product pest populations.

One of the major advantages of botanical insecticides is their multiple mechanisms of action. While most synthetic insecticides act on a single target site, botanical compounds generally affect multiple physiological processes in pests. This characteristic contributes to a slower development of resistance in pest populations (Dayan et al., 2009). For example, many essential oil constituents exhibit neurotoxic effects on the nervous system of pests while simultaneously inhibiting feeding behavior or disrupting developmental processes (Boate and Abalis, 2020). The role of botanical insecticides in sustainable agricultural systems is also increasing steadily. Today, sustainable agricultural practices are of great importance for reducing environmental impacts and conserving natural resources. Due to their low residue levels and rapid degradation in the environment, botanical insecticides are widely used in organic farming systems (Burtscher-Schaden et al., 2022). Moreover, these compounds are reported to contribute to biodiversity conservation and to have fewer adverse effects on natural enemy populations (Geiger et al., 2010).

Another reason for the increasing use of botanical insecticides in stored-product pest management is their ability to exhibit various biological activities. Botanical compounds may not only exhibit toxic effects against pests but also show repellent, antifeedant, and oviposition

deterrent activities. These multifunctional effects enable the control of pest populations at different life stages (Chaubey, 2012). Nevertheless, the use of botanical insecticides also presents certain limitations. The high volatility of essential oils, low stability, and sensitivity to environmental factors may reduce their effectiveness. Furthermore, the short-term activity of some botanical compounds may increase the need for repeated applications (Ragaei and Sabry, 2014). Therefore, the development of novel formulation techniques is of great importance to overcome these limitations.

In recent years, the development of advanced technologies such as nanotechnology and microencapsulation has played an important role in increasing the significance of botanical insecticides. These technologies improve the stability of active compounds, reduce volatility, and provide controlled release, thereby ensuring prolonged effectiveness (De Oliveira et al., 2014; Mustafa and Hussein, 2020). In addition, nanoformulations increase the bioavailability of botanical insecticides, enabling effective pest control at lower doses. Considering all these factors, it can be concluded that botanical insecticides constitute an important alternative for the management of stored-product pests and have become an integral component of sustainable pest management strategies. However, to enable the large-scale application of these compounds, further studies are required on the standardization of their efficacy, the development of suitable formulation techniques, and the evaluation of their long-term effects under field conditions (Nikolaou et al., 2021).

3. Modes of Action of Botanical Insecticides

The effectiveness of botanical insecticides against insect pests arises from the ability of their secondary metabolites to affect various physiological and biochemical processes. These compounds generally belong to different chemical groups such as monoterpenes, sesquiterpenes, phenols, alkaloids, and flavonoids, and exhibit multifunctional biological activities against pests (Isman, 2020; Nikolaou et al., 2021). The presence of multiple mechanisms of action in botanical insecticides provides an important advantage in delaying resistance development in pest populations (Dayan et al., 2009). The modes of action of botanical insecticides can generally be classified as neurotoxic effects, enzyme inhibition, respiratory effects, behavioral effects, and growth-regulating effects.

3.1. Neurotoxic Effects

One of the most important mechanisms of action of botanical insecticides is their effect on the nervous system of insect pests. Many constituents of essential oils can disrupt nerve transmission by affecting ion channels and neurotransmitter systems in nerve cells. This disruption may result in loss of coordination, paralysis, and death in pests (Tong and Coats, 2012). In particular, monoterpene compounds have been reported to exhibit neurotoxic effects by affecting gamma-aminobutyric acid (GABA) receptors in the insect nervous system. Inhibition of GABA receptors causes excessive stimulation of nerve cells, resulting in rapid mortality in pests (Tong and Coats, 2012; Isman, 2020). Furthermore, some botanical compounds are reported to disrupt the transmission of nerve impulses by affecting sodium and potassium ion channels, thereby causing paralytic effects in pests (Enan, 2001).

3.2. Acetylcholinesterase (AChE) Inhibition

Another important mechanism of action of botanical insecticides is the inhibition of the acetylcholinesterase (AChE) enzyme. The AChE enzyme regulates nerve transmission by breaking down acetylcholine in the nervous system. Inhibition of this enzyme leads to disruption of nerve transmission and continuous stimulation, ultimately resulting in paralysis and death in pests (Pavela, 2015). In particular, monoterpene compounds such as thymol, carvacrol, and eugenol have been reported to exhibit strong inhibitory effects on the AChE enzyme. These compounds produce high toxicity against stored-product pests, and their fumigant effects are largely associated with this mechanism (Pavela, 2015; Isman, 2020). AChE inhibition is an important characteristic because botanical insecticides can act through a mechanism similar to that of synthetic organophosphate and carbamate insecticides. However, the generally lower toxicity of botanical compounds provides an advantage in reducing environmental risks (Dayan et al., 2009).

3.3. Effects on Octopamine Receptors

Octopamine receptors are neurotransmitter receptors that play an important role in the insect nervous system and are absent in mammals. Therefore, the effects of botanical insecticides on octopamine receptors provide an important advantage in terms of selective toxicity (Enan, 2001). Some essential oil constituents have been reported to affect octopamine receptors, causing behavioral alterations, loss of coordination, and physiological disorders leading to

death in insects. This allows botanical insecticides to exhibit selective effects against target organisms (Enan, 2001; Isman, 2020).

3.4. Effects on the Respiratory System

Another important mechanism of action of botanical insecticides is associated with their effects on the respiratory system. Essential oils possessing fumigant activity may enter the respiratory system of insect pests, inhibit oxygen uptake, and disrupt energy metabolism (Pavela, 2015). Some botanical compounds have also been reported to interfere with mitochondrial functions, thereby inhibiting energy production and causing mortality in pests. This mechanism plays a particularly important role in compounds with fumigant activity (Tong and Coats, 2012).

3.5. Antifeedant Effects

One of the important biological effects of botanical insecticides is their antifeedant activity. Antifeedant compounds inhibit the feeding behavior of pests, thereby slowing their development or causing starvation that may result in death (Pavela, 2015). This effect generally occurs through the interaction of botanical compounds with the taste receptors of pests. Compounds such as azadirachtin are especially known for their strong antifeedant activity (Isman, 2020).

3.6. Repellent Effects

Repellent botanical compounds provide indirect protection by preventing pests from approaching products. These compounds generally cause behavioral changes by affecting the olfactory receptors of pests (Isman, 2020). Essential oil constituents exhibiting repellent activity against stored-product pests play an important role in controlling pest populations, particularly in storage environments (Nikolaou et al., 2021).

3.7. Oviposition Deterrent Effects

Some components of botanical insecticides can suppress population growth by inhibiting the oviposition behavior of pests. This effect is considered an important mechanism for long-term population control, especially in stored-product pests (Pavela, 2015). These compounds

affect the oviposition behavior of pests by preventing suitable surface selection and causing significant reductions in egg laying (Boate and Abalis, 2020).

3.8. Growth and Development Regulatory Effects

Some compounds of botanical insecticides can affect hormones regulating insect growth and development. In particular, interference with juvenile hormone and ecdysone hormone activity may lead to abnormalities in larval development and disruptions during the pupation process (Isman, 2020). As a result of this mechanism, effects such as deformities, delayed development, and reduced adult emergence can be observed. This enables botanical insecticides to effectively control pest populations over the long term (Dayan et al., 2009).

4. Types of Botanical Insecticides and Application Methods

Botanical insecticides constitute an important alternative for the control of stored-product pests due to the diversity of their biologically active compounds and their suitability for different application methods. These products are generally used in the form of essential oils, plant extracts, plant powders, and purified active compounds. In addition, their applicability through different methods such as fumigant, contact, and repellent applications enables effective control of pest populations at different life stages (Isman, 2020; Nikolaou et al., 2021).

4.1 Essential Oils

Essential oils are among the most widely used compounds in botanical insecticides. These oils are generally rich in monoterpenes, sesquiterpenes, and phenolic compounds and exhibit strong biological activity against pests (Isman, 2020). In particular, essential oils obtained from plants belonging to the Lamiaceae, Myrtaceae, Apiaceae, and Asteraceae families have been reported to possess high toxicity against stored-product pests (Regnault-Roger et al., 2012). The effects of essential oils on stored-product pests mainly occur through fumigant and contact activities. For example, essential oils obtained from plants such as Thymus vulgaris, Origanum vulgare, and Mentha piperita have been reported to produce high mortality rates against Sitophilus oryzae and Tribolium confusum (Pavela, 2015). Furthermore, some essential oils exhibit repellent effects, preventing pests from approaching stored products and thereby providing important protection during storage (Isman, 2020). The effectiveness of essential oils largely depends on their major constituents. Compounds such as thymol, carvacrol, eugenol, and pulegone are known to exhibit strong insecticidal activity against insect pests. These

compounds have been reported to exert neurotoxic effects on the nervous system, ultimately leading to pest mortality (Pavela, 2015).

4.2 Plant Extracts

Plant extracts are products obtained from different plant parts (leaves, seeds, roots, or bark) using solvents. Compared with essential oils, these extracts generally possess lower volatility and may therefore exhibit longer-lasting effects (Dayan et al., 2009). Plant extracts are known to exhibit toxic and growth-regulating effects against stored-product pests. In particular, the azadirachtin compound present in extracts of Azadirachta indica has been reported to possess strong antifeedant and growth-regulating activities (Isman, 2020). Neem extracts have also been reported to slow the developmental processes of stored-product pests and reduce pupation rates (Regnault-Roger et al., 2012). Another advantage of plant extracts is that different biologically active compounds can be obtained using different solvents, thereby contributing to increased efficacy of the extracts.

4.3 Plant Powders

Plant powders are obtained by grinding dried plant material and represent one of the oldest methods used in the control of stored-product pests. This method is particularly common in small-scale storage systems (Isman, 2020). Plant powders may exert both mechanical and chemical effects on insect pests. The mechanical effect damages the insect cuticle, causing water loss and eventually death. The chemical effect arises from the toxic activity of active compounds present in the plant material (Nikolaou et al., 2021). The main advantages of this method include low cost and ease of application, making it widely used especially in developing countries (Affognon et al., 2015).

4.4. Purified Botanical Compounds

To increase the efficacy of botanical insecticides, some active compounds are used in purified form. These compounds generally belong to specific chemical groups such as monoterpenes or alkaloids and exhibit high biological activity (Dayan et al., 2009). Compounds such as azadirachtin, rotenone, and pyrethrin are among the commercially used botanical insecticides. These compounds have been reported to exhibit high toxicity and broad-spectrum activity against stored-product pests (Isman, 2020). The use of purified compounds provides important advantages in terms of standardized dose application and better control of efficacy.

4.5. Application Methods

The effectiveness of botanical insecticides depends not only on their active compounds but also on the method of application. The principal application methods used in the management of stored-product pests include fumigant, contact, and repellent applications.

4.5.1. Fumigant Applications

Fumigant applications involve volatile compounds acting against pests in the gas phase. This method is widely used in the management of stored-product pests. The fumigant activity of essential oils is reported to occur through entry into the respiratory system of pests, thereby inhibiting oxygen uptake (Pavela, 2015). Fumigant applications possess important advantages because they can be effective against all life stages of stored-product pests. In addition, this method allows effective control over large storage areas (Isman, 2020).

4.5.2. Contact Applications

Contact applications involve the direct interaction of botanical insecticides with insect pests. This method is generally performed through surface applications or direct spraying (Nikolaou et al., 2021). Contact-active botanical compounds are reported to disrupt the cuticular structure of pests, causing water loss and eventually mortality (Dayan et al., 2009).

4.5.3. Repellent Applications

Repellent applications provide indirect protection by preventing insect pests from approaching products. This method plays an important role particularly in preventing pest invasion in storage environments (Isman, 2020). Repellent botanical compounds cause behavioral alterations by affecting the olfactory receptors of insect pests. This effect may also prevent pests from laying eggs on products (Nikolaou et al., 2021).

5. Current Technological Developments

Among the most important factors limiting the use of botanical insecticides are low stability, high volatility, sensitivity to environmental conditions, and short-term activity. To overcome these limitations, advanced technologies such as nanotechnology, microencapsulation, and improved extraction techniques have been developed in recent years. These technologies

increase the efficacy of botanical insecticides and provide longer-lasting and controlled effects against stored-product pests (De Oliveira et al., 2014; Pavoni et al., 2019).

5.1. Nanoformulations

Nanotechnology is considered one of the fastest-developing fields in the improvement of botanical insecticides. Nanoformulations enable active compounds to be prepared as nanoparticles, thereby increasing bioavailability and efficacy (Benelli et al., 2020). One of the most important advantages of nanoformulations is the increased surface area of active compounds. This allows more effective interaction with insect pests and enables high efficacy at lower doses (Pavoni et al., 2019). In addition, nanoformulations reduce the evaporation of essential oils, increase stability, and improve resistance against environmental factors (De Oliveira et al., 2014).

Nanoformulations have been reported to play an important role in enhancing the fumigant and contact effects of botanical insecticides against stored-product pests. In particular, essential oils formulated as nanoemulsions exhibit longer-lasting biological activity and greater effectiveness in controlling pest populations compared with conventional formulations (Benelli et al., 2020).

5.1.1. Nanoemulsions

Nanoemulsions are systems obtained by mixing oil and water phases as nanometer-sized droplets. These systems significantly improve the water solubility and bioavailability of essential oils (Pavoni et al., 2019). Nanoemulsions have been reported to exhibit high insecticidal activity against stored-product pests and to be effective at lower doses compared with conventional emulsions. Moreover, their high stability contributes to maintaining efficacy during storage (De Oliveira et al., 2014).

5.1.2. Nanocapsules

Nanocapsules are systems obtained by encapsulating active compounds within polymeric or lipid structures. These systems allow controlled release of active compounds, thereby providing prolonged effects (Campos et al., 2015). Nanocapsule systems protect essential oils against environmental factors such as light, oxygen, and temperature, thereby increasing their

stability. This enables botanical insecticides to remain effective for longer periods in storage environments (De Oliveira et al., 2014).

5.2. Microencapsulation Technologies

Microencapsulation is a technology obtained by entrapping active compounds within micrometer-sized capsules. This method reduces the evaporation of essential oils and enables the controlled release of active compounds (Jyothi et al., 2010). Microencapsulation technology has been reported to increase the stability and prolong the biological efficacy of botanical insecticides. Thanks to this technology, active compounds remain effective for longer periods in storage environments, resulting in more successful control of pest populations (Campos et al., 2015). In addition, microencapsulation reduces environmental losses by enabling the controlled delivery of active compounds to the target surface. This allows more efficient use of botanical insecticides (Jyothi et al., 2010).

5.3. Controlled Release Systems

Controlled release systems are technologies that enable the slow and continuous release of active compounds over a specific period. These systems increase the long-term efficacy of botanical insecticides and reduce the need for repeated applications (Campos et al., 2015). Controlled release systems have been reported to provide important advantages in the management of stored-product pests. These systems make it possible to suppress pest populations over extended periods (Pavoni et al., 2019). This technology plays a particularly important role in improving the efficacy of essential oils with fumigant properties.

5.4. Novel Extraction Technologies

One of the important factors determining the efficacy of botanical insecticides is the extraction method. Novel technologies developed as alternatives to conventional extraction methods increase the yield of active compounds and enable the production of purer products (Chemat et al., 2017).

5.4.1. Ultrasound-Assisted Extraction

Ultrasound-assisted extraction is a method that uses high-frequency sound waves to disrupt plant cell walls. This technique shortens the extraction time and increases the yield of active compounds (Chemat et al., 2017).

5.4.2. Microwave-Assisted Extraction

Microwave-assisted extraction enables the rapid heating of plant cells, allowing active compounds to be obtained in a shorter time. This method is widely used because it reduces energy consumption while providing high extraction efficiency (Chemat et al., 2017).

5.4.3. Supercritical CO_2 Extraction

Supercritical CO_2 extraction is a method performed using carbon dioxide under high pressure. This technique reduces solvent usage and provides an environmentally friendly extraction approach. Furthermore, high-purity active compounds can be obtained using this method (Herrero et al., 2010).

5.5. Smart Formulation Systems

Smart formulation systems developed in recent years are systems capable of regulating the release of active compounds in response to environmental conditions. These systems can control the release of active compounds depending on factors such as temperature, pH, or humidity (Campos et al., 2015). Smart formulation systems contribute to increasing efficacy by enabling botanical insecticides to reach target organisms more effectively. In addition, these systems have been reported to reduce environmental losses and contribute to the development of more sustainable pest management strategies (Benelli et al., 2020).

6. Advantages, Limitations, and Future Perspectives

Botanical insecticides offer significant advantages as environmentally friendly alternatives in the management of stored-product pests. However, the widespread use of these products also presents several limitations. Therefore, the advantages, limitations, and future potential of botanical insecticides should be evaluated together.

6.1 Advantages of Botanical Insecticides

One of the most important advantages of botanical insecticides is their environmentally friendly nature. Unlike synthetic insecticides, botanical compounds are generally biodegradable and do not persist in the environment for long periods. This contributes to reducing environmental pollution and helps preserve natural ecosystems (Isman, 2020; Benelli et al., 2020). Another important advantage is the generally low toxicity of botanical insecticides. These compounds exhibit lower toxicity toward non-target organisms compared with synthetic insecticides, thereby contributing to biodiversity conservation (Regnault-Roger et al., 2012). Moreover, this characteristic allows their widespread use in organic farming systems.

The multiple mechanisms of action of botanical insecticides provide an important advantage in delaying resistance development in pest populations. While most synthetic insecticides target a single site, botanical compounds can simultaneously affect the nervous system, respiratory system, and behavioral processes of pests (Dayan et al., 2009). This enables more effective suppression of pest populations. Another advantage of botanical insecticides is that they can be obtained from local plant resources. Particularly in developing countries, the use of local plant species enables the development of low-cost pest management strategies. This provides important economic benefits for small-scale producers (Affognon et al., 2015). In addition, botanical insecticides have considerable potential for use in Integrated Pest Management (IPM) programs. Their compatibility with biological control agents contributes to the development of sustainable pest management strategies (Nikolaou et al., 2021).

6.2. Limitations of Botanical Insecticides

One of the most important factors limiting the use of botanical insecticides is their low stability and high volatility. The sensitivity of essential oils to environmental factors is considered a major limitation affecting their efficacy. In particular, temperature, light, and oxygen may rapidly degrade active compounds (Isman, 2020). Another important limitation is the variability in the efficacy of botanical insecticides. The chemical composition of botanical products may vary depending on environmental conditions, harvest time, and extraction methods. This variability complicates product standardization (Regnault-Roger et al., 2012). The short-term effectiveness of botanical insecticides is also considered an important limitation. This increases the need for repeated applications and may raise application costs (Benelli et al., 2020).

Furthermore, stability problems may occur during the commercial-scale production and storage of some botanical compounds. This is considered one of the major factors complicating the development of commercial formulations (Campos et al., 2015). Another limitation of botanical insecticides is that, in some cases, they may exhibit lower efficacy than synthetic insecticides. Therefore, they may not provide sufficient control alone under conditions of high pest populations (Dayan et al., 2009).

6.3. Future Perspectives

The future potential of botanical insecticides is directly associated with the development of new technologies. In particular, advances in nanotechnology and microencapsulation technologies improve the stability of botanical insecticides and enable prolonged activity (De Oliveira et al., 2014). One of the most important future research priorities is the standardization of active compounds to enhance the efficacy of botanical insecticides. Standardization of the chemical composition of botanical products is essential for their commercial application (Isman, 2020). Next-generation formulation technologies have significant potential to increase the use of botanical insecticides. In particular, the development of controlled release systems and smart formulation technologies will allow botanical insecticides to remain effective for longer periods (Campos et al., 2015).

In future studies, the effects of botanical insecticides on non-target organisms should also be investigated in greater detail. Furthermore, evaluating their long-term environmental impacts is important for sustainable use (Benelli et al., 2020). To promote the wider use of botanical insecticides in stored-product pest management, long-term field trials should be increased. Verification of laboratory results under field conditions will support the commercial application of these products (Nikolaou et al., 2021). Finally, the integration of botanical insecticides into IPM programs will play an important role in the development of sustainable agricultural systems. This approach will contribute to reducing synthetic insecticide use and enhancing environmental sustainability (Regnault-Roger et al., 2012).

7. Conclusion

Botanical insecticides have significant potential as environmentally friendly and sustainable alternatives for the management of stored-product pests. Today, the intensive use of synthetic insecticides has resulted in resistance development, environmental pollution, and risks to human health, making the development of alternative pest management strategies essential. In this context, botanical insecticides have gained an important role in sustainable pest management strategies due to their natural origin and biodegradable characteristics (Isman, 2020; Nikolaou et al., 2021).

The multiple mechanisms of action of botanical insecticides enable the control of pest populations at different life stages. Furthermore, their various biological activities, including repellent, antifeedant, fumigant, and growth-regulating effects, make them suitable for use in Integrated Pest Management programs (Dayan et al., 2009). Nevertheless, botanical insecticides still present certain limitations, such as low stability, high volatility, and difficulties in standardization. Nanoformulations, microencapsulation systems, and novel extraction technologies developed in recent years have contributed substantially to overcoming these limitations by enhancing the efficacy of botanical insecticides. In particular, controlled release systems and smart formulation technologies have enabled botanical insecticides to remain effective for longer periods in stored-product pest management (Benelli et al., 2020; De Oliveira et al., 2014). For the wider future application of botanical insecticides, further efforts are required regarding the standardization of active compounds, the development of appropriate formulation techniques, and the expansion of long-term field studies. In addition, detailed investigations on the effects of these products on non-target organisms are essential for environmental sustainability.

In conclusion, the increasing importance of botanical insecticides in the management of stored-product pests will contribute significantly to the development of sustainable agricultural practices. With the integration of modern technologies into this field, botanical insecticides are expected to become more effective, safer, and economically viable pest management tools in the future..

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IN VITRO EVALUATION OF CU-DOPED SILICON NITRIDE COMPOSITES

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ABSTRACT

Recent years have seen the development of new materials that can adapt to biological systems (biocompatible) and possess the mechanical properties desired by the body as a significant topic of interest in the biomedical field. To reduce infections caused by bacteria adsorbed during implantation, surface modifications with inorganic antibacterial agents are required. Based on this, the main objective of our study, designed with a multidisciplinary approach involving Biology Biotechnology, and Materials Science, is to evaluate the morphological properties, cytotoxic activities, and the effect of ROS on the biocompatibility of copper (Cu) -doped silicon nitride (Si_3N_4) composites.

When the results of XTT, Proliferation, and ROS analysis of the composites were evaluated together, it was observed that concentrations of 20-60-250 µg/mL could be considered as products with the potential to form implant raw materials, which is the hypothesis of the project. When the results of the ROS analysis performed using flow cytometry were evaluated, it was determined that Si_3N_4-Cu produced a significant scavenging effect, which is the elimination of reactive oxygen species, during the 24-48-72 hour time intervals (20-60-250 µg/mL).

Keywords: Biocompatibility, L929, ROS Scavenging Effect, Si_3N_4-Cu (Copper-doped Silicon Nitride)

BAKIR KATKILI SİLİKON NİTRÜR KOMPOZİTLERİN İN VİTRO DEĞERLENDİRMESİ

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ÖZET

Son yıllarda, biyolojik sistemlerle yüksek uyum sağlayan ve ideal mekanik özelliklere sahip yeni nesil malzemelerin geliştirilmesi biyomedikal alanın öncelikli konularından biri haline gelmiştir. Özellikle implantasyon sonrası gelişen ve bakteriyel adsorpsiyon kaynaklı enfeksiyon riskini minimize etmek adına, yüzeylerin inorganik antibakteriyel ajanlarla modifiye edilmesi kritik bir ihtiyaçtır.Bu gereksinimden yola çıkarak kurgulanan çalışmamızda; Biyoteknoloji ve Malzeme Bilimi disiplinlerini bir araya getiren bir yaklaşımla sentezlenen Bakır (Cu) katkılı Silisyum Nitrür (Si_3N_4) kompozitlerin morfolojik özellikleri, sitotoksik profilleri ve biyouyumluluk üzerindeki Reaktif Oksijen Türleri (ROS) etkisi kapsamlı bir şekilde değerlendirilmiştir.

XTT, Proliferasyon ve ROS analizi sonuçları birlikte değerlendirildiğinde; 20, 60 ve 250 µg/mL konsantrasyonların, çalışmamızın temel hipotezi olan "yüksek potansiyelli implant hammadde adayı" kriterlerini karşıladığı gözlenmiştir. Akış sitometrisi (Flow Cytometry) ile gerçekleştirilen analizler; Si_3N_4-Cu kompozitlerinin 24, 48 ve 72 saatlik periyotlarda, serbest radikalleri bertaraf eden kayda değer bir ROS süpürme (scavenging) etkisi oluşturduğunu kanıtlamıştır.

Anahtar Kelimeler: Biyouyumluluk, L929, ROS Süpürme Etkisi, Si_3N_4-Cu (Bakır katkılanmış Silikon nitrit).

1. Introduction

Silicon nitride (Si_3N_4) holds a privileged position among modern engineering ceramics thanks to its superior mechanical, thermal, and chemical properties. The high hardness and wear resistance provided by its covalent bond structure make this material indispensable, especially for structural applications under heavy loads (Du et al., 2022). Due to its low thermal expansion coefficient, it exhibits excellent thermal shock resistance against severe temperature fluctuations and remains one of the rare materials capable of maintaining its mechanical strength even at high temperatures (Heimann, 2021). Furthermore, it demonstrates high resistance to corrosive environments and acidic/basic solutions. While it has traditionally been widely used in high-performance industrial areas such as gas turbines, engine parts, and bearings, it has recently drawn attention for its potential in the biomedical field (Pezzotti and McEntire, 2024). Si_3N_4 is evaluated as a promising material for next-generation orthopedic implants and dental applications due to its biocompatible nature and antibacterial properties; in particular, its surface chemistry, which supports interaction with bone tissue and the formation of hydroxyapatite, makes this ceramic a strong alternative to metallic implants (Boschetto et.al., 2024).

Silicon nitride (S_3N_4) is a non-oxide ceramic that is rarely seen in nature; however, it can occur naturally as it has been found in meteoric rock particles. Although synthetic S3N4 was first developed by Deville and Wöhler in 1859, it has only gained significant popularity and become the subject of detailed research in recent years. Silicone nitride spinal spacers and intervertebral fusion cage products have received CE and FDA clearance based on animal studies and standard compliance requirements (Zou et. al., 2023).

Due to its superior mechanical properties and biocompatibility, S3N4 has been recognized as a potential biomedical material since the 1980s, particularly for orthopedic applications. To date, various S_3N_4 spinal spacers and intervertebral fusion cage products have received CE and FDA clearance based on animal studies and standard compliance requirements. Meanwhile, it has been extensively studied as a material that could extend the lifespan of knee joints and prosthetic hips (Heimann, 2021).

Nanoparticles often exhibit unique physico-chemical properties that differ significantly from their counterparts at the macroscopic scale. At the nanoscale, the surface-to-volume

ratio changes substantially, resulting in higher reactivity compared to the bulk material (Kalidas et al., 2025).

Another advantageous property of S_3N_4 for medical applications is its antibacterial characteristic, which is essential for orthopedic implants. When bacteria colonize the surface of an implant by forming a biofilm, these pathogens exhibit resistance to host immune mechanisms and systemic antibiotics (Marin et. al., 2023).

The effectiveness of metallic nanoparticles used against human pathogenic microbes has made them highly attractive in biomedical fields. In particular, metallic nanoparticles have gained prominence in ex-situ and more favorable settings to promote faster reactions and increase production yield. These metallic nanoparticles are generally divided into two groups as noble and non-noble metallic groups, depending on the nanoparticle species. Metallic nanoparticles are cost-effective, environmentally friendly, non-toxic, and reduce the accumulation of hazardous waste. Furthermore, the green synthesis of metallic nanoparticles is safer for biomedical and environmental applications (Wang et al., 2024). Various approaches have been proposed to reduce infections caused by bacteria adsorbed during the implantation process, such as surface modification with inorganic antibacterial agents. Ag, ZnO, and CuO are inorganic antibacterial agents with proven strong antibacterial activity and desirable biocompatibility. The application of nano-scale Cu can lead to superior antibacterial performance compared to their micron-sized counterparts due to their higher surface area (Priya et al., 2023; Fulaz et al., 2019).

In this study, the crystal structure, morphology, and functional groups of silicon nitride composites doped with different percentages of silver and copper were analyzed using X-ray diffractometry (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared (FTIR) spectroscopy, respectively. The cytotoxic effect of the synthesized composite material was evaluated using the L929 healthy mouse fibroblastic cell line, which is suitable for cytotoxic analysis according to ISO standards (10993-5) (Cannelle et al., 2019). Cell viability analyses were performed using XTT assays. In line with the project objectives, Reactive Oxygen Species (ROS) analyses were conducted by evaluating the optimization studies obtained from the XTT results. Thus, the inflammation-inducing potential of the synthesized silver-doped silicon nitride composites was assessed by determining the ROS levels they may generate within the cells. ROS levels in the cells were

measured using the flow cytometry method, and these levels were simultaneously visualized using confocal microscopy to confirm the flow cytometry results.

2. Research And Findings

Synthesis and characterization

Within the scope of the study, S_3N_4 was synthesized via carbothermal reduction and nitridation/carburization process. Coper dopped S_3N_4 were synthesized using the Lee and Meisel (1988) method, incorporating S_3N_4 produced via carbothermal reduction. (Arik et al., 2003; Pricop et al., 2025). The crystal structure of the synthesized biocompatible composites was elucidated using X-ray diffraction (XRD), and their morphology was analyzed via scanning electron microscopy (SEM). Furthermore, the functional groups involved in the nanoparticle synthesis were characterized using Fourier-transform infrared (FTIR) spectroscopy.

Cell Culture and Biocompatibility Analyses

The XTT assay is based on the reduction of tetrazolium salts into colored formazan compounds, depending on cell viability (active mitochondria). The reduced formazan compounds are water-soluble, and their density can be measured spectrophotometrically at determined wavelengths; this density is directly proportional to the number of metabolically active cells (Godwin et al., 1995). The synthesized Cu-doped Silicon Nitride (S_3N_4) composites were prepared in a liquid culture medium at a concentration of 10 mg/mL. Their cytotoxic effects against L929 cell lines were evaluated in 96-well culture plates using the serial dilution method. Following the completion of 24, 48, and 72-hour incubation periods, the experimental groups were photographed using an Inverted Microscope, and the MTT assay was performed to assess cell viability.

Cell Proliferation Analayses

Nanomaterials can negatively affect cell proliferation. To this end, the composite material synthesized during the study was applied to the L929 cell line, and its effects on cell proliferation were evaluated. Based on the results obtained via the XTT method, cells

were seeded into 24-well cell culture plates. Following the completion of the incubation periods, the experimental groups were analyzed by performing cell counts.

Evaluation of ROS Formation Efficiency of Cu-Doped Silicon Nitride Composites

The procedure was performed according to the ROS Kit (Abcam, USA) protocol. Cells were stained with DCFDA in the culture medium and incubated at 37°C for 30 minutes. Following the completion of the incubation periods (1-6 hours), the samples were analyzed using flow cytometry [(DCF was excited by a 488 nm laser and detected at 535 nm (typically FL1)]. The fold change between the control and treated samples was determined using the mean fluorescence intensity (MFI).

Determination of the ROS Generation Potential of Composites Using Confocal Microscopy

Adherent cells in standard cell culture medium were grown to an appropriate density on a substrate suitable for live-cell imaging. The cells were stained by adding diluted DCFDA solution and incubated in the dark at 37°C for 45 minutes with the diluted DCFDA solution. Analysis was performed at 535 nm using a Confocal Microscope.

İstatistiksel Analiz

In this study, cell viability analyses were performed in at least triplicate. The proliferative effects of the extracts at determined concentrations were examined for significant differences using Student's t-test ($p < 0.05$) (Lee et al., 2026). Statistical analysis was carried out in GraphPad Prism version 8.0.2 (GraphPad Software, California, USA).

3. Results and Discussion

The XRD pattern of pure Si_3N_4 powder is shown in black below. It is observed that the main peaks of Si_3N_4 are located within the 20°–35° range. Upon examining the XRD analysis, the peaks at 43.8° and 25.2° are found to correspond to the (111) crystal plane of Cu, respectively (Chen et al., 2024). Furthermore, the functional groups involved in the nanoparticle synthesis were analyzed using Fourier-transform infrared (FTIR) spectroscopy (Figure 1). The Si-N stretching vibrations exhibited peaks at 510 and 820 cm^{-1}, and the characteristic Si_3N_4 structure was identified by a sharp decrease at 1000 cm^{-1} (Avotina et al., 2018).

Akter et al. (2025) investigated the structural and photocatalytic properties of CuO nanostructures and concluded that the bands located at 432, 500, 580, and 675 cm^-1 belong to the monoclinic phase of CuO. Similarly, in our study, the FT-IR spectrum of Cu-Si_3N_4 exhibited peaks around 438, 518, and 590 cm^-1 (Akter et al., 2025).

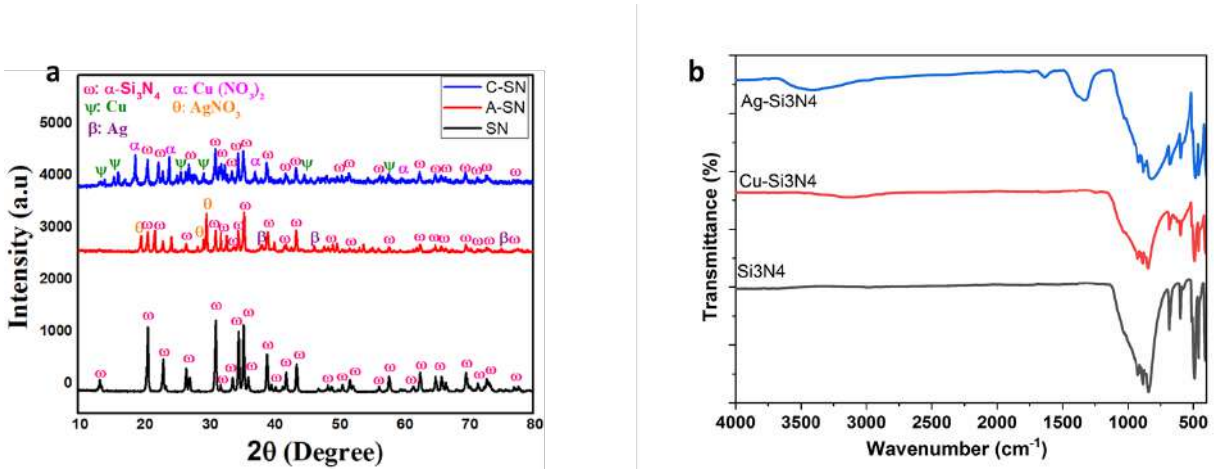


Figure 1. XRD and FTIR Analysis of Cu-doped Samples.

The structural, morphological, and elemental characteristics of the synthesized Cu-doped Si_3N_4 composites were comprehensively evaluated using XRD, SEM (at 1000X and 3000X magnifications), and EDS analysis, respectively (Figure 2 and Figure 3).

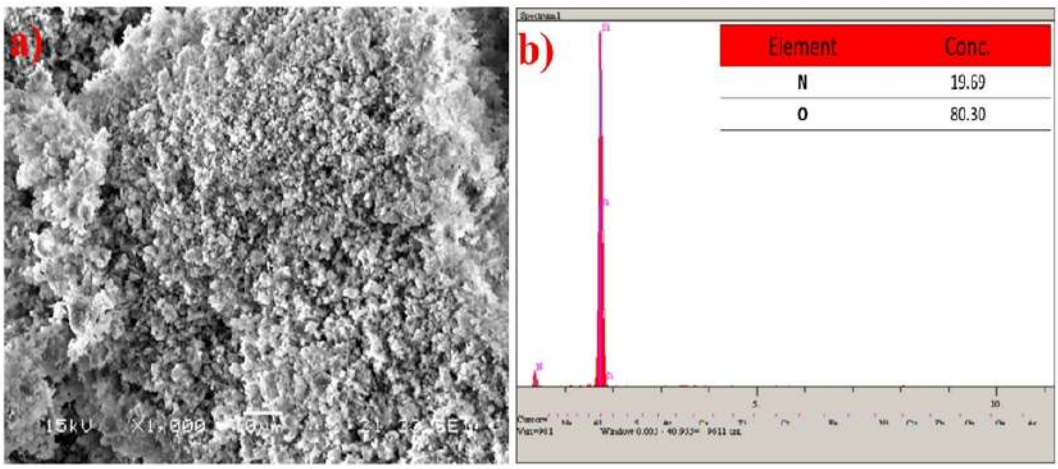


Figure 2. a) SEM images and **b)** EDS results of the Si_3N_4 samples.

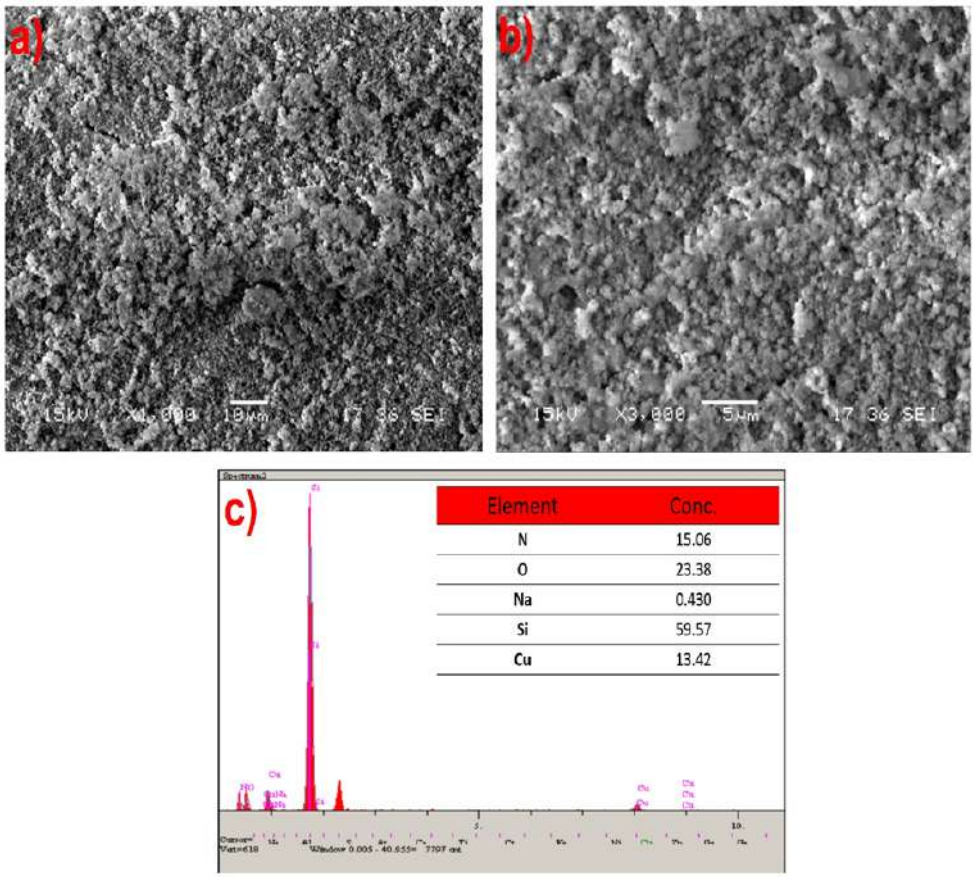


Figure 3. a) SEM image at 1000X, **b)** SEM image at 3000X, and **c)** EDS results of Cu- Si_3N_4 samples.

Biocompatibility Analyses

When evaluating the cell viability (%) graph of Si 3 N4 treatment on L929 cell lines, viability was analyzed to be over 50% at concentrations of 125 µg/mL at 24 hours, 250 µg/mL at 48 hours, and 62.5 µg/mL at 72 hours. The half-maximal inhibitory concentration (IC 50) values were determined to be an average of 185, 360, and 50 µg/mL at 24, 48, and 72 hours, respectively (Figure 4).

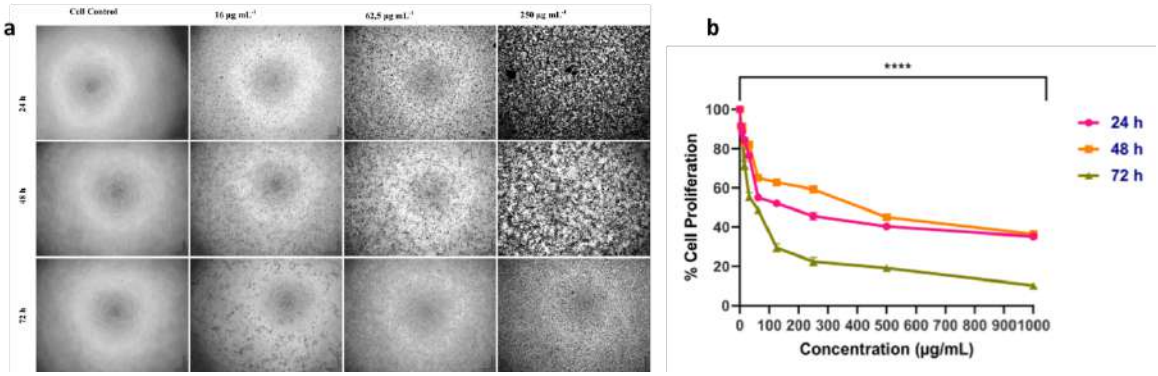


Figure 4. a) Inverted microscopy images (10X) of L929 cells following treatment with silicon nitride (Si_3N_4), **b)** Cell viability (%) following the application of silicon nitride (Si_3N_4) composites.

Upon analyzing the copper-doped silicon nitride (Si_3N_4-Cu) experimental group, cell viability was determined to be above 250 µg/mL across all three time intervals specified in the study. The confirmation of the experimental results was provided using inverted microscopy. The inverted microscopy (10X) imaging results, obtained prior to the XTT application, are consistent with the calculated cell viability percentages and IC_{50} analysis result. The IC_{50} values were found to be 240, 300, and 165 µg/mL, respectively (Figure 5).

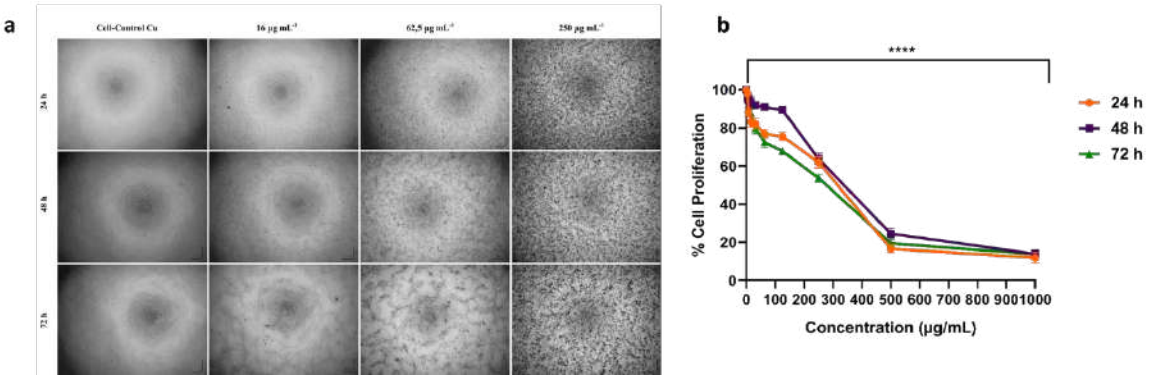


Figure 5. a) Inverted microscopy images (10X) of L929 cells following treatment with copper-doped silicon nitride (Si_3N_4 -Cu) composites. **b)** Cell viability (%) following the application of silicon nitride-dopped Cu (Si_3N_4-Cu) composites.

Zou et al. (2024) loaded titanium onto silicon nitride (Si_3N_4-Ti) in their study and dental implant material was coated with the material. In a study on human bone marrow mesenchymal stem cells (hBMSCs), a 10% cell counting Kit-8 solution (CCK-8) was used. The analysis conducted on days 1-3-5-7 of the study demonstrated the beneficial effect of the Si_3N_4 coating on hBMSCs. The CCK-8 assay also confirms that Si_3N_4-Ti is non-toxic to

hBMSCs and supports their proliferation to some extent (Zou et al., 2024). Yang et al., (2025), in their study, used bovine aortic endothelial cells (BAECs) and Raw 264. The biocompatibility of gold-functionalized graphene oxide (GO-Au) nanocomposites was analyzed using mouse macrophages and human mesenchymal stem cells (MSCs) **(Yang et. al.)**

Cell Proliferation Analayses

In the proliferation study conducted using silicon nitride (Si_3N_4), proliferation levels close to those of the control group were observed after incubation periods of 24, 72, and 120 hours, particularly at a concentration of 62.5 µg/mL (Figure 6).

Upon evaluating the proliferation analyses following the treatment with copper-doped silicon nitride (Si_3N_4-Cu) composite materials, a proliferative effect was observed at a concentration of 250 µg/mL compared to the control group across all three time intervals. The imaging results (10X) obtained using inverted microscopy prior to cell counting further support the findings of the proliferation study (Figure 7).

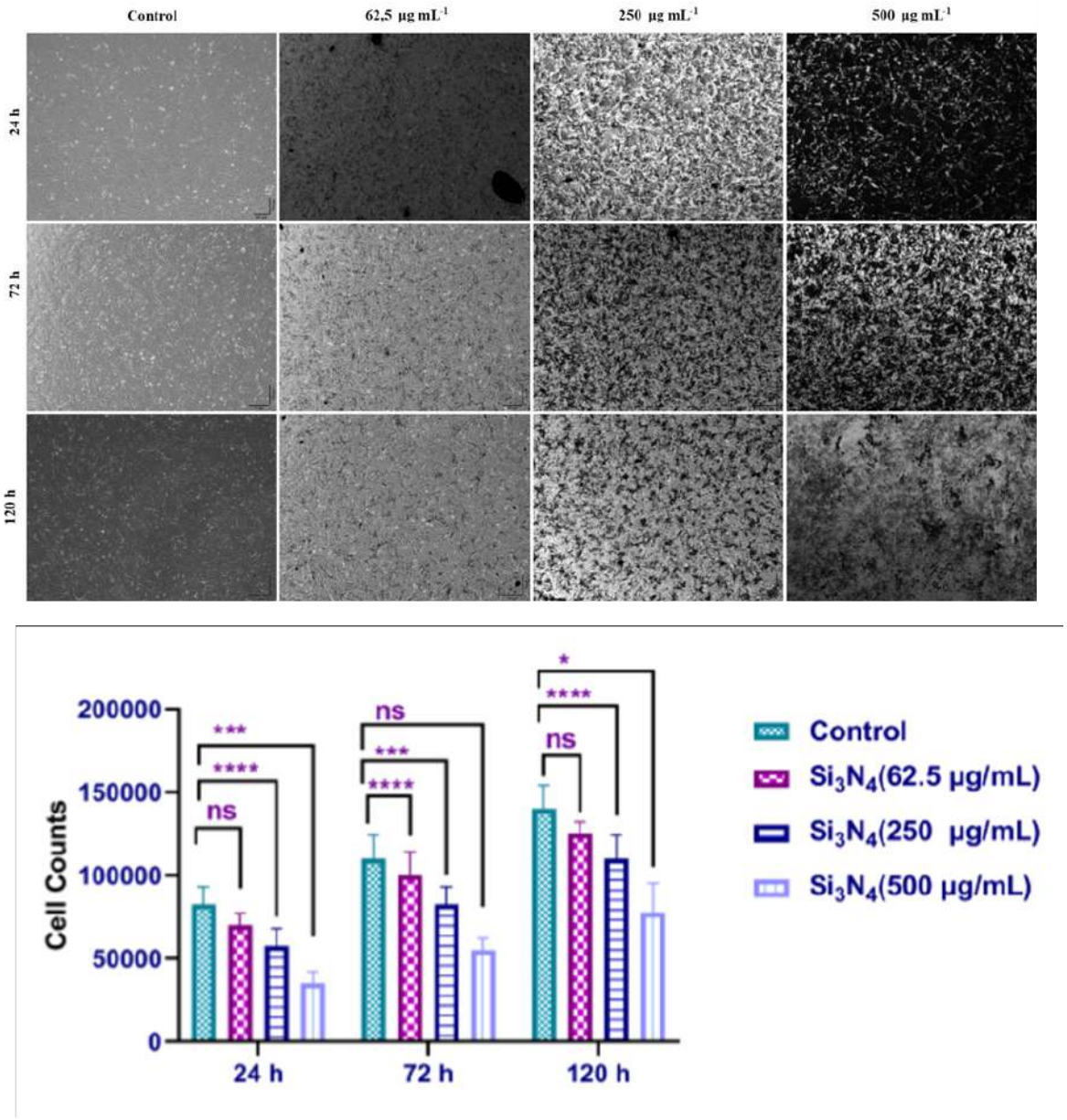


Figure 6. Cell proliferation after silicon nitride (Si_3N_4) composite application.

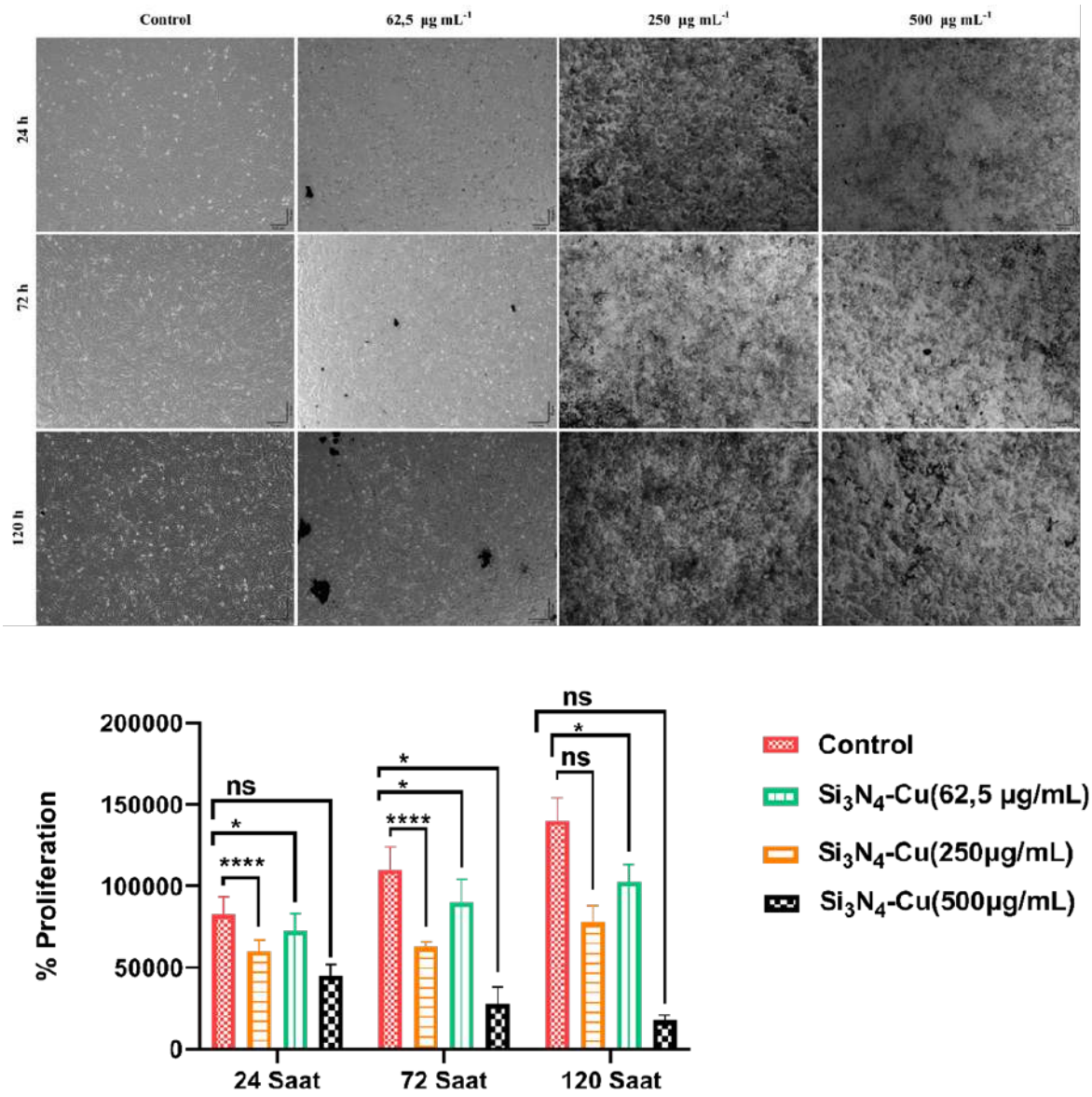


Figure 7. Cell Proliferation Following the Application of Copper-Doped Silicon Nitride (Si_3N_4 -Cu) Composites.

Evaluation of ROS Formation Efficiency

The results of the study indicate that 24 and 48-hour applications of silicon nitride (Si_3N_4) exhibit a significant scavenging effect on ROS activity, particularly at a

concentration of 250 µg/mL (Figure 18a-18b). However, following 72 hours of treatment, it was observed that the scavenging effect of Si_3N_4 at the specified concentrations (20, 60, and 250 µg/mL) decreased (Figure 9)

In the study of copper-doped silicon nitride (Si_3N_4-Cu), it was observed that the 60 µg/mL concentration exhibited a scavenging effect on ROS generation at 24 and 48 hours compared to the negative control. While the average ROS formation rate in the negative control was 50%, it was determined that the Si_3N_4-Cu treatment reduced these rates to 14% and 24% at the 24th and 48th hours, respectively (Figure 10).

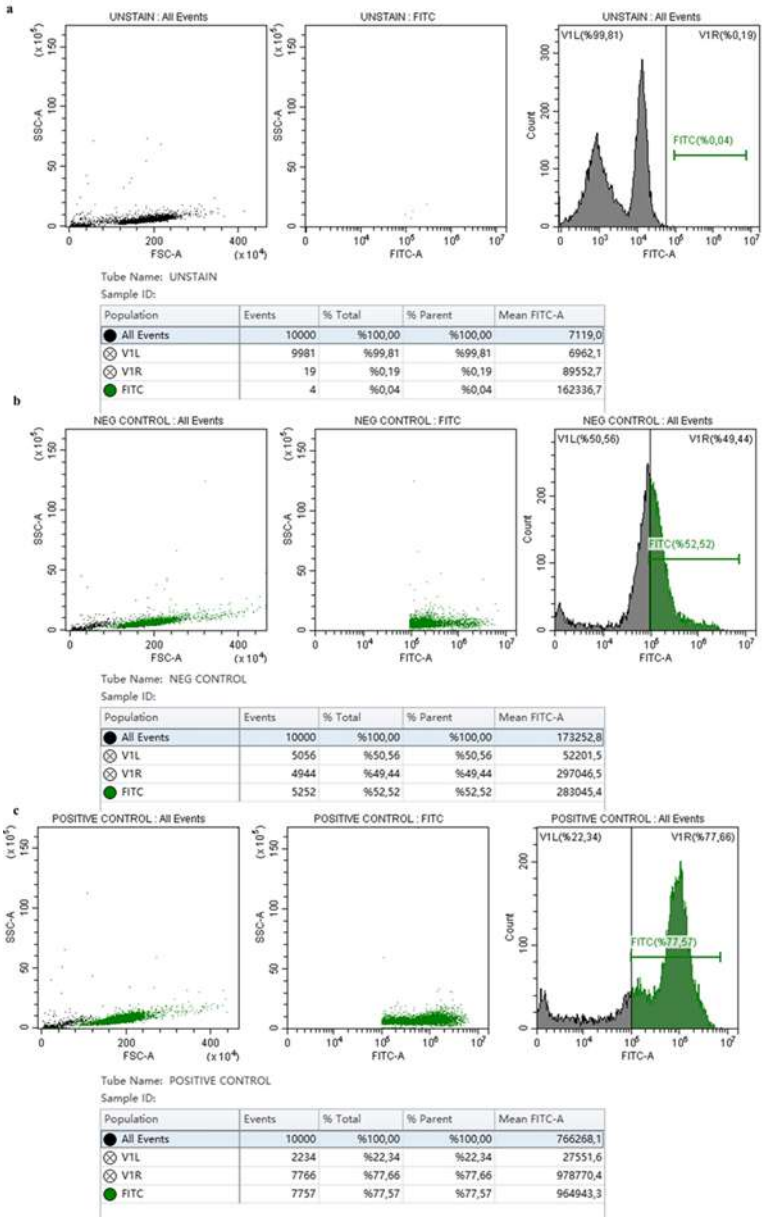


Figure 8. Investigation of ROS generation mechanisms using flow cytometry. a) Unstained cell group, b) negative control, c) positive control.

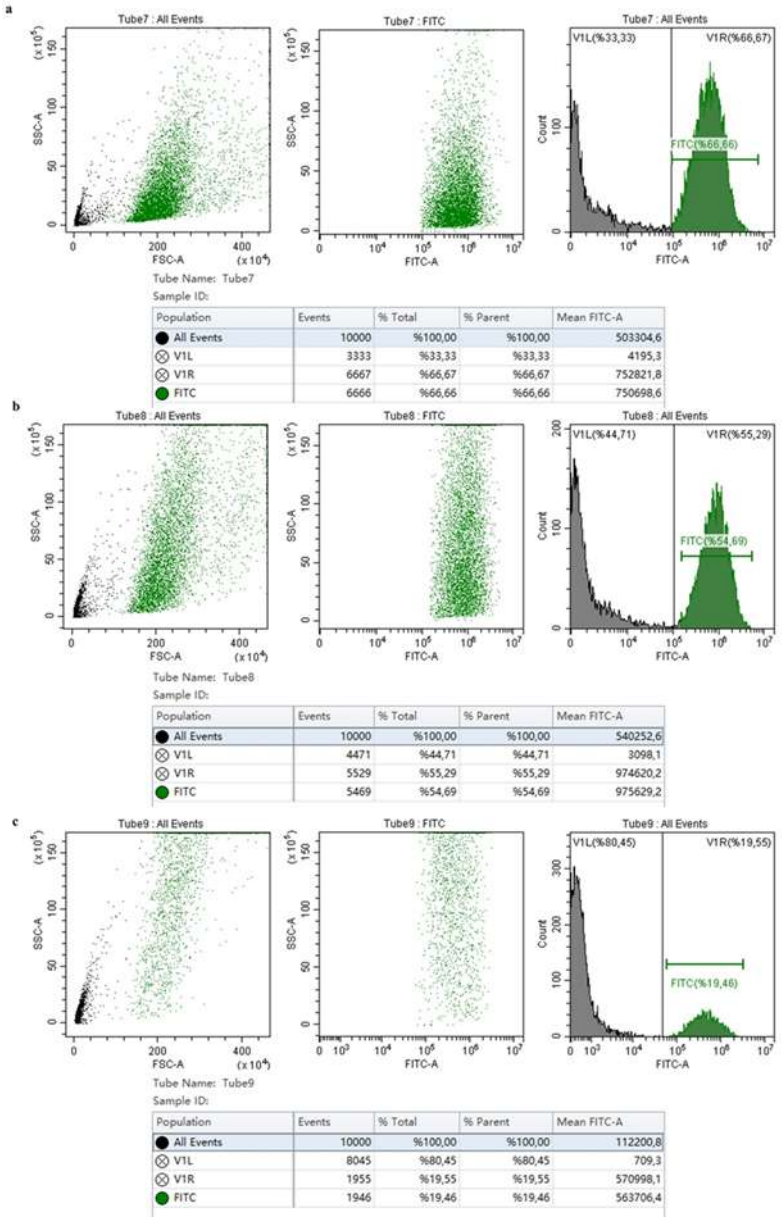


Figure 9. 48-hour treatment with Si3 N4 : a) Si_3N_4 at 20 µg/mL, b) S Si_3N_4 at 60 µg/mL, and c) Si_3N_4 at 250 µg/mL.

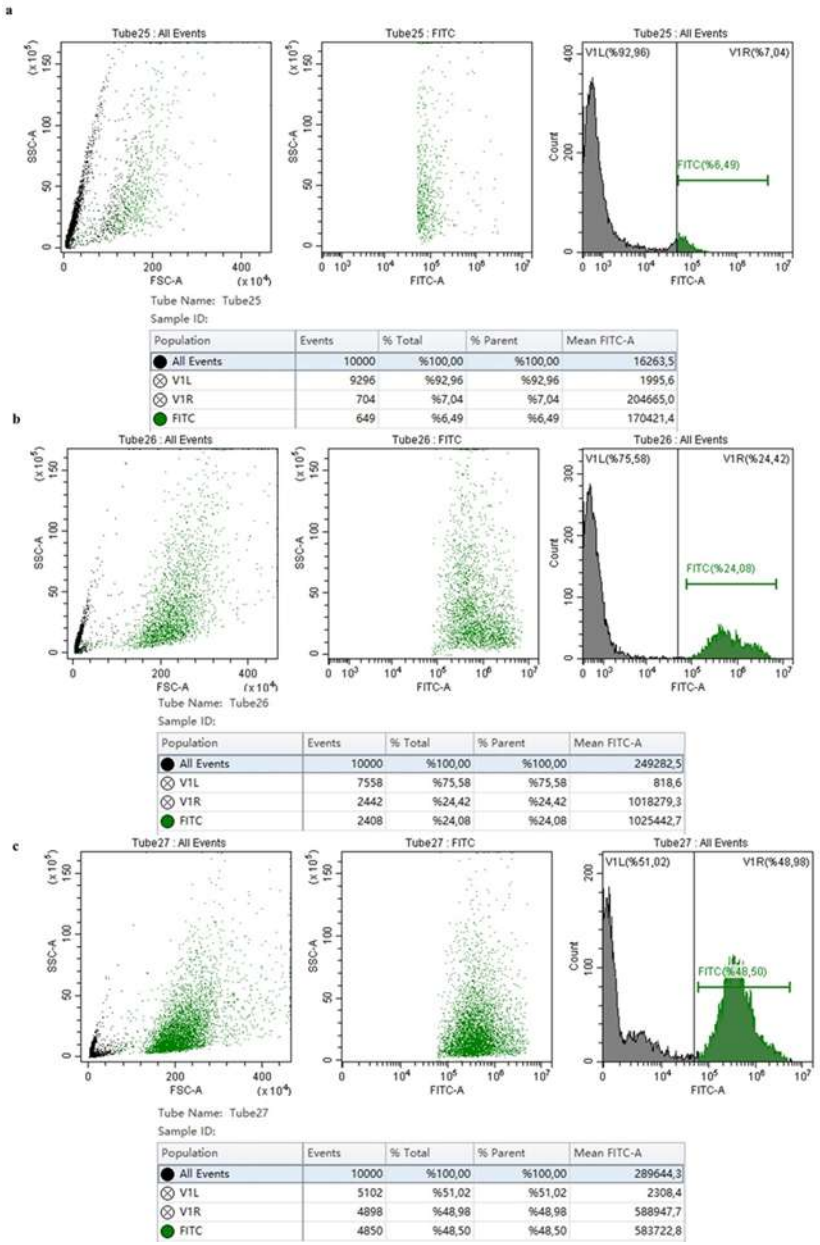


Figure 10. 48-hour treatment with Si_3N_4 -Cu: a) Si_3N_4-Cu at 20 µg/mL, b) Si_3N_4 -Cu at 60 µg/mL, and c) Si_3N_4 -Cu at 250 µg/mL

In a study conducted by Lal et al. (2018), PBMNC (peripheral blood mononuclear cell) lines were exposed to low and high particle doses for 24 hours, with volumetric concentrations of 0.5 and 50 µm 3 per cell, respectively. Fluorescence measurements were obtained using a 96-well plate reader, and further visualization of ROS generation in cells was performed using fluorescence microscopy. It was reported that neither nanoscale nor micron-scale Si_3N_4 particles induced significant reactive oxygen species (ROS) production (Lal et al., 2018).

A comprehensive review of the literature revealed a lack of detailed ROS analysis specifically focusing on the application Si_3N_4-Cu composites.

Confocal microscopic analysis (10X) of intracellular ROS production

Based on the results obtained from the flow cytometry analysis, it was confirmed that the application of 250 µg/mL silicon nitride (Si_3N_4) for 48 hours induced reactive oxygen species (ROS) formation in approximately 20% of the total cell population

The application of Si_3N_4-Cu at a concentration of 60 µg/mL exhibited a scavenging effect on ROS generation compared to the control group. The designated experimental groups were evaluated by comparison with the positive control group. The findings are consistent with and serve to confirm the results obtained from the flow cytometry analysis.

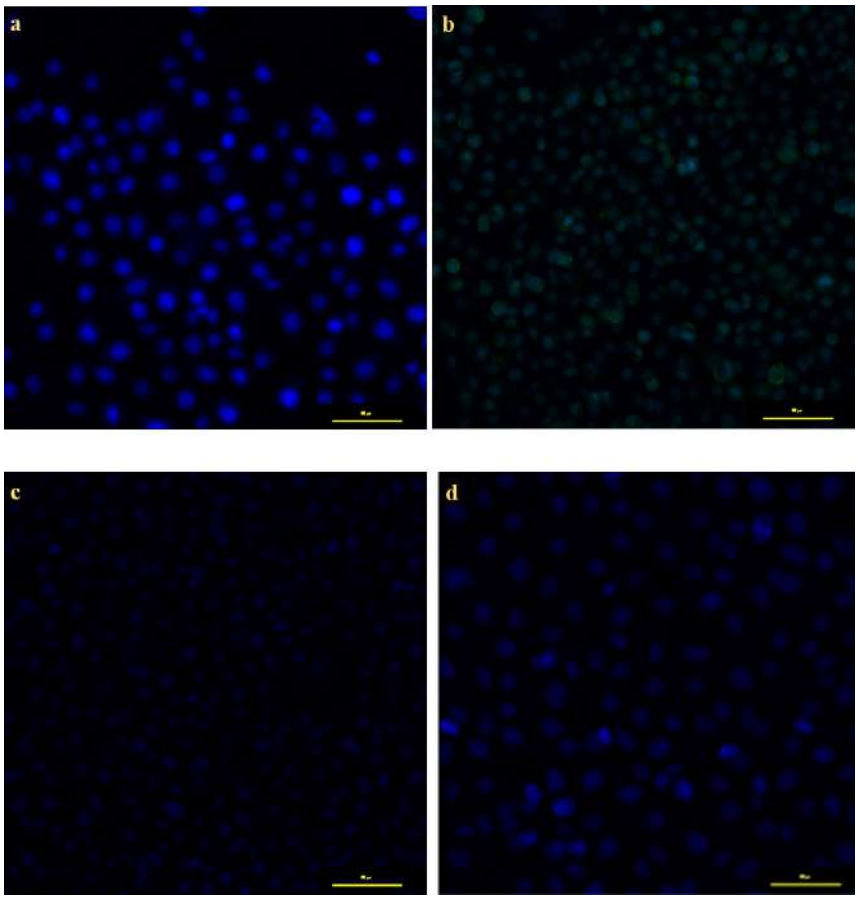


Figure 11. **a)** Cell Control, **b)** Positive Control, **c)** Si_3N_4-250 µg/mL 48 h **d)** Si_3N_4-Cu 60 µg/mL 48 h

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EVALUATION OF THE UTILIZATION POTENTIAL OF NUTRIENT-RICH COLD-PRESSED BLACK CUMIN (*NIGELLA SATIVA* L.) SEED CAKE IN MODEL FOODS

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Abstract

With the growing emphasis on sustainability and waste reduction in food production, increasing attention has been directed toward the nutritional valorization of plant-based press cakes generated during oilseed processing. Black cumin (*Nigella sativa* L.) press cake, obtained after oil extraction by cold pressing, is a valuable by-product due to its high protein, dietary fiber, and bioactive compound content. However, studies addressing its direct use in human nutrition and providing a comprehensive evaluation of its nutritional value remain limited. Current findings indicate that black cumin press cake has the potential to enhance the nutritional profile of food products as a plant-based source of protein and dietary fiber. In addition, it may contribute significantly to antioxidant capacity due to its phenolic compound content. Nevertheless, its characteristic aromatic profile, slightly bitter taste, and dark color may limit consumer acceptance, particularly in light-colored food products. Therefore, determining appropriate levels of incorporation and processing strategies is essential for its successful application in food formulations. In this study, three different model food products, namely a yogurt topping powder, an oat–black cumin bar, and crackers, were developed to evaluate the utilization potential of black cumin press cake. Sensory evaluations revealed that varying incorporation levels influenced aroma, color, and overall acceptability, while acceptable sensory properties could be achieved through appropriate formulation strategies. In conclusion, cold-pressed black cumin press cake can be considered not only as a by-product but also as a promising alternative ingredient with high nutritional value and functional properties when properly formulated. This study provides an applied perspective on the use of black cumin press cake within sustainable food systems.

Keywords: BC-Cake, Nutritional value, Plant-based protein, Dietary fiber, Functional food applications.

BESLEYİCİ ÖZELLİKLERE SAHİP SOĞUK PRES ÇÖREK OTU KÜSPESİNİN MODEL GIDALARDA KULLANIM POTANSİYELİNİN DEĞERLENDİRİLMESİ

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Özet

Gıda üretiminde sürdürülebilirlik ve atık azaltma yaklaşımlarının önem kazanmasıyla birlikte, yağlı tohum işleme süreçleri sonucunda ortaya çıkan bitkisel küspelerin beslenme açısından değerlendirilmesine yönelik çalışmalar artış göstermektedir. Soğuk pres yöntemiyle yağ üretimi sonrası elde edilen çörek otu (*Nigella sativa* L.) küspesi, yüksek protein, diyet lifi ve biyoaktif bileşen içeriği ile dikkat çeken önemli bir yan üründür. Ancak bu küspenin doğrudan insan beslenmesinde kullanımına ve besin değerinin bütüncül olarak değerlendirilmesine yönelik çalışmalar sınırlıdır. Mevcut bulgular, çörek otu küspesinin bitkisel protein ve lif kaynağı olarak ürünlerin besinsel profilini geliştirme potansiyeline sahip olduğunu göstermektedir. Ayrıca içerdiği fenolik bileşikler sayesinde antioksidan kapasite açısından da önemli bir katkı sağlayabileceği bildirilmektedir. Bununla birlikte, kendine özgü aromatik yapısı, hafif acımsı tadı ve koyu renk tonu, özellikle açık renkli ürünlerde duyusal kabulü sınırlayabilecek unsurlar arasında yer almaktadır. Bu nedenle, çörek otu küspesinin gıda formülasyonlarında kullanımında uygun oranların ve işleme stratejilerinin belirlenmesi önem taşımaktadır. Bu çalışma kapsamında, çörek otu küspesinin model gıdalardaki kullanım potansiyelini ortaya koymak amacıyla yoğurt üzerine eklenen fonksiyonel un, yulaf–çörek otu bar ve kraker olmak üzere üç farklı model ürün geliştirilmiştir. Yapılan duyusal değerlendirmeler, küspenin kullanım oranına bağlı olarak ürünlerin aroma, renk ve genel beğenilirlik özelliklerinde değişimler oluşturduğunu ve uygun formülasyonlarla kabul edilebilir duyusal özelliklerin sağlanabildiğini göstermektedir. Sonuç olarak, soğuk pres çörek otu küspesi, uygun formülasyon stratejileri ile yalnızca bir yan ürün olmaktan çıkarak besin değeri yüksek ve fonksiyonel özellikler sunan alternatif bir bileşen olarak değerlendirilebilir. Bu çalışma, çörek otu küspesinin sürdürülebilir gıda sistemleri kapsamında kullanımına yönelik uygulamalı bir yaklaşım sunmaktadır.

Anahtar Kelimeler: Çörek Otu Küspesi, Besin değeri, Bitkisel protein, Diyet lif, Fonksiyonel Gıda Uygulamaları.

"Bu çalışma, Adana Alparslan Türkeş Bilim ve Teknoloji Üniversitesi Bilimsel Araştırma Projeleri Koordinasyon Birimi tarafından 25103012 numaralı proje kapsamında desteklenmiştir."

1. Giriş

Soğuk pres yağ üretimi son yıllarda tüketici tercihlerindeki doğallık eğilimiyle birlikte önemli ölçüde büyümüş, bu süreçte yağ ekstraksiyonu sonrası elde edilen küspe miktarı da artış göstermiştir. Çörek otu (*Nigella sativa* L.), *Ranunculaceae* familyasına ait, Orta Doğu, Güney Asya ve Kuzey Afrika'da yüzyıllardır hem baharat hem de geleneksel tıbbi bitki olarak kullanılan yıllık otsu bir bitkidir (Ahmad et al., 2013; Zaky et al., 2021). Tohumların biyoaktif bileşen açısından zengin yapısı, soğuk pres yağ endüstrisini cazip kılmış ancak aynı zamanda büyük miktarlarda besin açısından değerli küspe üretilmesine yol açmıştır (Łopusiewicz et al., 2022).

Çörek otu tohumları yaklaşık %22-40 sabit yağ, %18-23 protein, %8 diyet lifi ve %25-40 karbonhidrat içermektedir (Bashir et al., 2020; Zaky et al., 2021). Soğuk pres işlemi sırasında tohumun %15-25'i oranında artık yağ küspede kalırken protein, lif, mineral ve timokinon, fenolikler ve tokoferoller gibi biyoaktif bileşenler konsantre hale gelmektedir (Hallouch et al., 2024; Rabiej-Kozioł and Szydłowska-Czerniak, 2024; Çavdaroğlu et al., 2025). Bu bileşim profili, çörek otu küspesini fonksiyonel gıda bileşeni olarak son derece cazip kılmaktadır (Yabacı Karaoğlan, 2025).

Literatürde çörek otu küspe ununun ekmek (Yüksel et al., 2023), makarna (Krawęcka et al., 2022), glutensiz ürünler (Różyło et al., 2021) ve kurabiye (Batool et al., 2024) gibi fırın ürünlerinde kullanımı incelenmiş; protein, lif ve antioksidan kapasitesi üzerindeki olumlu etkileri raporlanmıştır (Yüksel et al., 2023). Łopusiewicz et al. (2022), çörek otu küspesinin fermente bitkisel kefir benzeri içecek üretimine de uygun olduğunu göstermiştir. Bununla birlikte, küspenin doğrudan insan beslenmesine yönelik pratik formülasyonlar kapsamında, yoğurt gibi süt ürünleriyle kombinasyonu, bar ve kraker gibi fırınlanmış atıştırmalıklardaki kullanımı ve bu uygulamalara ilişkin gerçek tüketici kabul verileri oldukça sınırlı kalmaktadır.

Bu çalışmanın amacı, soğuk pres çörek otu küspesinin (1) yoğurt üzeri fonksiyonel un (topping), (2) yulaf-çörek otu atıştırmalık bar ve (3) tohum kraker olmak üzere üç farklı model gıdadaki kullanım potansiyelini duyusal analiz yöntemiyle değerlendirmek ve ürün kategorisine özgü optimum küspe konsantrasyonlarını belirlemektir. Elde edilen bulgular, çörek otu küspesinin döngüsel ekonomi çerçevesinde sürdürülebilir gıda sistemlerine entegrasyonuna katkı sağlamayı hedeflemektedir.

2. Materyal ve Yöntem

2.1. Ham Maddeler

Çalışmada hammadde olarak Burdur ili Bucak ilçesinden temin edilen, soğuk sıkım yöntemiyle yağı alınmış çörek otu (*Nigella sativa* L.) küspesi kullanılmıştır. Pelet hâlindeki küspe, laboratuvar tipi bıçaklı değirmende öğütülmüş ve 500 µm altı partikül boyutuna elenerek homojenizasyon sağlanmıştır. Öğütülen un, mikrobiyolojik güvenlik amacıyla 125°C'de 10 dakika ön ısıl işleme tabi tutulmuştur.

Diğer ham maddeler olarak yulaf ezmesi, domates salçası (en az %32 kuru madde), biber salçası (en az %28 kuru madde), soğuk sıkım extra virgin zeytinyağı, iyotlu sofra tuzu, kekik, kabuksuz ayçekirdeği, kabak çekirdeği, karnıyarık otu tozu, keten tohumu ve tam yağlı sade yoğurt kullanılmıştır. Tüm bileşenler yerel marketlerden standart ticari ürünler olarak temin edilmiştir.

2.2. Atıştırmalık Bar Üretimi

Atıştırmalık bar üretiminde öncelikle çörek otu küspesi, yulaf ezmesi, tuz ve kekik homojen olacak şekilde karıştırılmıştır. Ayrı bir kapta domates ve biber salçası zeytinyağı ile emülsiyon hâline getirilmiştir. Kuru ve yaş karışımlar birleştirildikten sonra 25 mL su ilavesiyle homojen hamur elde edilmiştir. Her formülasyondan 4 adet, yaklaşık 4 cm × 8 cm × 1,5 cm boyutlarında şekillendirilmiş ve iki aşamalı pişirme uygulanmıştır: ilk aşamada 150°C'de 10 dakika, ardından 10. dakikada ters yüz edilerek 120°C'de 10 dakika daha pişirilmiştir. Ürünler fırın teli üzerinde oda sıcaklığına soğutulmuş ve 4±1°C'de muhafaza edilmiştir. Formülasyonlar Tablo 1'de sunulmaktadır; küspe oranları kuru madde bazında hesaplanmış olup fırınlama sırasında buharlaşan su miktarı dikkate alınmamıştır.

Tablo 1. Atıştırmalık Bar Formülasyonları

Bileşen	AB-K (Kontrol)	AB-F1	AB-F2	AB-F3	AB-F4
Çörek otu küspesi (g)	0,00	5,00	10,00	15,00	20,00
Yulaf ezmesi (g)	60,00	55,00	50,00	45,00	40,00
Domates salçası (g)	18,00	18,00	18,00	18,00	18,00
Biber salçası (g)	2,00	2,00	2,00	2,00	2,00
Zeytinyağı (g)	18,00	18,00	18,00	18,00	18,00
Tuz (g)	1,50	1,50	1,50	1,50	1,50
Kekik (g)	0,22	0,22	0,22	0,22	0,22
Su (mL)	25,00	25,00	25,00	25,00	25,00
Toplam-yaş ağırlık (g)	99,72	99,72	99,72	99,72	99,72
Çörek otu oranı* (KM)	**%0**	**%5**	**%10**	**%15**	**%20**

**Kuru madde bazında çörek otu küspesi oranı (fırınlama sonrası su buharlaşması dikkate alınarak hesaplanmıştır).*

2.3. Tohum Kraker Üretimi

Tohum kraker üretiminde kuru bileşenler önce homojen olarak karıştırılmıştır. Bağlayıcılık sağlamak amacıyla keten tohumu, 80-85°C'deki sıcak su ile muamele edilerek oda sıcaklığında 20 dakika bekletilmiş ve jelleşmesi sağlanmıştır. Jelleşen keten tohumu ve zeytinyağı kuru karışıma yavaşça eklenerek homojen bir kıvam elde edilmiştir. Hazırlanan karışım 10 cm × 21 cm ebadında ve 1 cm kalınlığında tepsiye yayılmış; çatal yardımıyla yüzeye delikler açılmış ve 8 eşit parçaya bölünmüştür. Pişirme önceden ısıtılmış fırında 150°C'de toplam 20 dakika süreyle gerçekleştirilmiş olup 10. dakikada ürünler ters yüz edilerek homojen pişirme sağlanmıştır. Formülasyonlar Tablo 2'de sunulmaktadır.

Tablo 2. Tohum Kraker Formülasyonları

Bileşen	TK-K (Kontrol)	TK-F1	TK-F2	TK-F3	TK-F4
Çörek otu küspesi (g)	0,00	5,00	10,00	15,00	20,00
Ayçekirdeği (g)	40,00	35,00	30,00	25,00	20,00
Kabak çekirdeği (g)	25,00	25,00	25,00	25,00	25,00
Karnıyarık otu tozu (g)	3,00	3,00	3,00	3,00	3,00
Kekik (g)	0,22	0,22	0,22	0,22	0,22
Zeytinyağı (g)	8,00	8,00	8,00	8,00	8,00
Tuz (g)	2,00	2,00	2,00	2,00	2,00
Keten tohumu (g)	5,00	5,00	5,00	5,00	5,00
Su-sıcak (mL)	50,00	50,00	50,00	50,00	50,00
Toplam-yaş ağırlık (g)	83,22	83,22	83,22	83,22	83,22
Çörek otu oranı* (KM)	**%0**	**%6**	**%12**	**%18**	**%24**

**Kuru madde bazında çörek otu küspesi oranı (fırınlama sonrası su buharlaşması dikkate alınarak hesaplanmıştır).*

2.4. Yoğurt Üzeri Fonksiyonel Toz Uygulaması

Çörek otu küspesinin süt ürünleriyle kombinasyon potansiyelini değerlendirmek amacıyla yoğurt üzeri fonksiyonel toz uygulaması tercih edilmiştir. Bu yaklaşım, küspenin pratik kullanım olanaklarını ve tüketici kabulünü doğrudan test etmeyi hedeflemiştir. Mikrobiyolojik güvenlik için 125°C'de 10 dakika pastörize edilen ve <500 µm partikül boyutuna sahip çörek otu unu, şeffaf mika tadım kaplarında hazırlanan 2 tatlı kaşığı sade yoğurt (tam yağlı) üzerine 1 çay kaşığı (~2-3 g) düzeyinde eklenerek tüketiciler tarafından değerlendirilmiştir. Tek konsantrasyonun test edilmesi, bu ürünün niteliği gereği, diğer ürünlerin aksine çok basamaklı ikame yerine pratik tek porsiyonluk uygulamaya daha uygun olmasından kaynaklanmaktadır.

2.5. Duyusal Analiz

Duyusal değerlendirme, Adana Alparslan Türkeş Üniversitesi Gıda Mühendisliği Bölümünde standardize edilmiş bireysel test alanlarında, kontrollü koşullarda (20-22°C, normal aydınlatma, sessiz ortam) gerçekleştirilmiştir. Çalışmaya üniversite personeli ve öğrencilerinden oluşmuş toplam 16 panelist (kadın/erkek: %78/%22; yaş aralığı: 23-58 yıl) davet edilmiş, katılım durumuna bağlı olarak atıştırmalık bar değerlendirmesinde n=16, tohum kraker ve yoğurt topping değerlendirmelerinde n=15 panelist yer almıştır.

Değerlendirmeler 9 noktalı hedonik skala (1 = hiç beğenmedim, 9 = çok beğendim) kullanılarak görünüş, koku, tat, lezzet, genel beğeni ve tercih etme kriterleri üzerinden yapılmıştır (Aigster et al., 2011; Stone et al., 2020). Panelistlere test öncesi gerekli bilgilendirme yapılmış ve onamları alınmıştır. Örnekler rastgele üç haneli kodlarla sunulmuş, tadımlar arasında su ve sade kraker ile ağız temizliği sağlanmıştır.

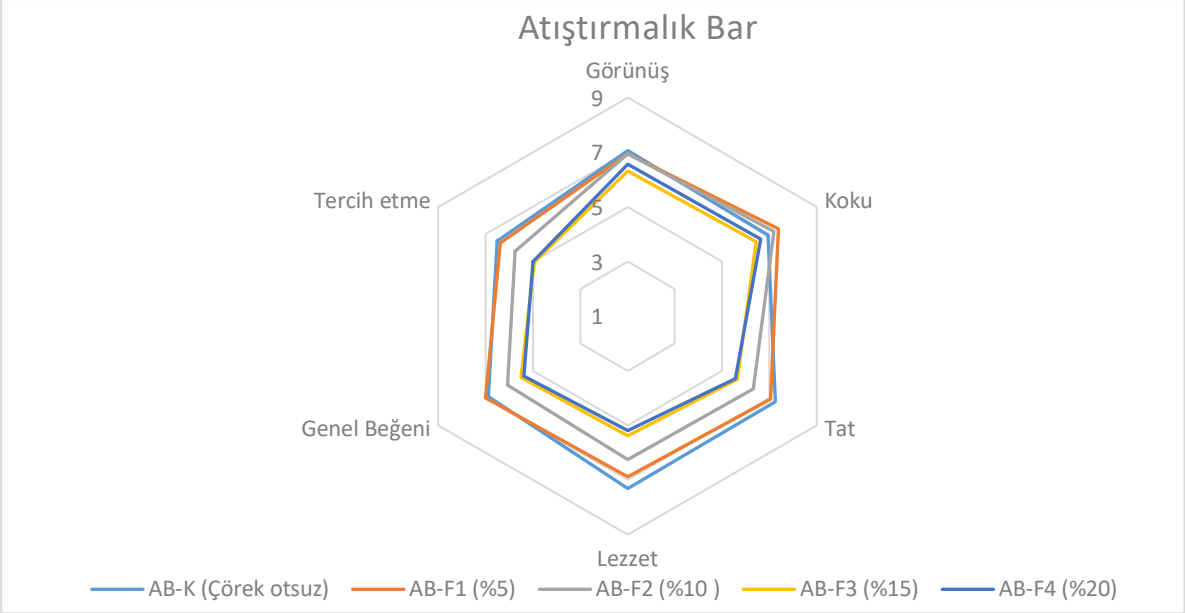
3. Bulgular ve Tartışma

3.1. Atıştırmalık Bar Duyusal Analiz Sonuçları

Atıştırmalık bar formülasyonlarına ait duyusal analiz sonuçları Şekil 1'de verilmiştir. Çörek otu küspesi içermeyen kontrol grubu (AB-K), tat (7,25±1,48) ve lezzet (7,31±1,35) kriterlerinde en yüksek puanları almıştır. %5 küspe içeren AB-F1 formülasyonu ise koku açısından kontrol grubunu geride bırakmış (7,38±1,54 > 6,94±2,11) ve genel beğeni puanı kontrol grubuna yakın seyretmiştir (7,00±1,51 ve 6,88±1,78). Bu bulgu, düşük konsantrasyonlarda çörek otu küspesinin barın aromasına kendine özgü olumlu bir katkıda bulunduğunu gösterebilir.

Küspe oranı arttıkça tüm kriterlerde düzenli bir düşüş gözlenmiştir. %15 ve %20 konsantrasyonlarında panelistler acılık şikayetlerini belirgin biçimde dile getirmiş, tercih etme puanı sırasıyla 4,94±2,02 ve 5,00±2,10 düzeyine gerilemiştir. Bu eğilim, literatürde benzer formülasyonlar için raporlanan bulgularla örtüşmektedir. Kamandloo et al. (2023) muffin çalışmalarında %3-6 aralığının duyusal kabul açısından optimum olduğunu bildirirken, Batool et al. (2024) kurabiye formülasyonlarında %10-15 oranında en yüksek duyusal puanlara ulaşılabileceğini belirtmiştir. Söz konusu sonuçlar, çörek otu küspesi unu kullanımının atıştırmalık bar ürünleri için %5-10 aralığının ticari potansiyel taşıdığına işaret etmektedir.

Şekil 1. Atıştırmalık Bar Formülasyonlarına Ait Duyusal Analiz Sonuçları (9-Puanlı Hedonik Skala, n=16)

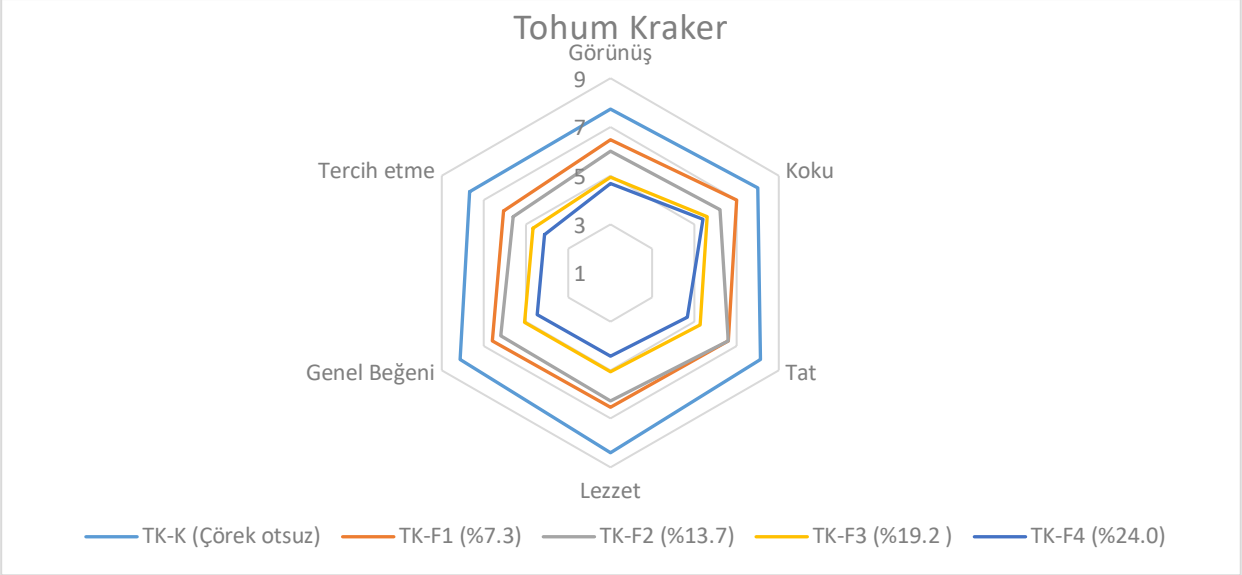


3.2. Tohum Kraker Duyusal Analiz Sonuçları

Tohum kraker formülasyonlarına ait duyusal sonuçlar Şekil 2'de yer almaktadır. Kontrol grubu (TK-K), tüm kriterler bakımından en yüksek puanları almış (7,47-8,07 aralığı) ve bu sonuç, temel tohum kraker formülasyonunun tüketici tarafından oldukça beğenildiğini ortaya koymuştur. Çörek otu küspesi ilavesiyle birlikte kabul edilebilirlik skorları sürekli ve anlamlı biçimde azalmış; %24 konsantrasyonundaki TK-F4'te tüm kriterlerde en düşük puanlara ulaşılmıştır (4,13-4,93 aralığı).

Bu düşüşün başlıca nedeni olarak yüksek konsantrasyonlarda artan acılık ve yoğun aroma etkileri öne çıkmaktadır; panelistler özellikle TK-F3 ve TK-F4 için tuzluluk ve acılık kombinasyonundan kaynaklanan olumsuz geri bildirimler iletmiştir. Benzer eğilimler Różyło et al. (2021) tarafından glutensiz ekmek formülasyonlarında %10 küspe eklendiğinde belgelenmiş; yüksek oranlarda sert aroma nedeniyle kabul edilebilirliğin düştüğü bildirilmiştir. Krawęcka et al. (2022) ise makarnadaki üst kullanım sınırını %20 olarak tanımlamıştır. Söz konusu bulgular, tohum kraker matrisinin çörek otu küspesinin baskın aromasına karşı sınırlı bir maskeleme kapasitesine sahip olduğunu düşündürmektedir; bununla birlikte %6 konsantrasyonunun (TK-F1) genel beğeni bakımından 6,93±1,67 ile hâlâ kabul edilebilir aralıkta kaldığı görülmüştür

Şekil 2. Tohum Kraker Formülasyonlarına Ait Duyusal Analiz Sonuçları (9-Puanlı Hedonik Skala, n=15)

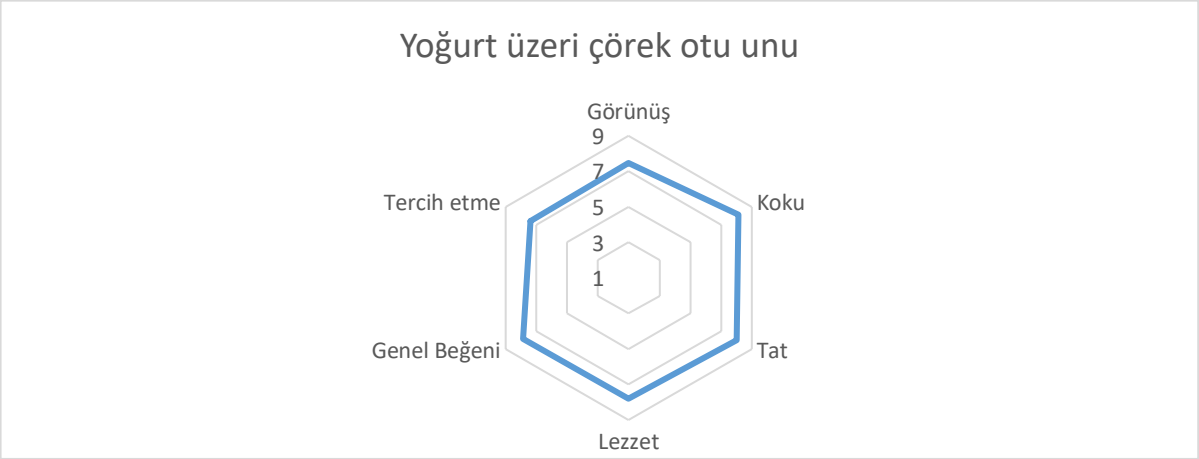


3.3. Yoğurt Üzeri Çörek Otu Unu (Topping) Duyusal Analiz Sonuçları

Yoğurt üzeri çörek otu unu uygulamasına ilişkin duyusal analiz sonuçları Şekil 3'te sunulmaktadır. Tek konsantrasyonda (~2-3 g) test edilen bu uygulama, üç ürün kategorisi arasında en yüksek duyusal kabul edilebilirliği sergilemiştir. Özellikle koku (7,56±1,59) ve görünüş (7,31±1,78) kriterleri belirgin biçimde ön plana çıkmış, panelistlerin %86,7'si (15 panelistten 13'ü) ürüne 7 ve üzeri puan vermiştir. Bazı panelistler 'yoğurt tadını baskılamıyor' ve 'günlük olarak tüketilebilir' şeklinde olumlu geri bildirimler iletmiştir.

Bu sonuçlar, çörek otu küspesinin süt ürünleriyle anlamlı bir tat uyumu sergilediğine işaret etmektedir. Yoğurdun kremalı ve hafif ekşimsi yapısının, küspenin kendine özgü acımsı notlarını dengeleyerek bu uyumu kolaylaştırdığı düşünülmektedir. Literatürde süt ürünleri ile yapılmış çörek otu formülasyonlarına rastlanmamış olsa da, Zaky et al. (2021) küspe proteinlerinin fonksiyonel özelliklerinin çeşitli gıda sistemlerinde olumlu tekstür ve duyusal katkı sağladığını vurgulamıştır. Mevcut çalışmanın yoğurt topping tadım bulguları, çörek otu küspesinin süt bazlı matrislere, puding ve benzeri kremalı ürünler dahil, başarıyla entegre edilebileceğine dair uygulamalı kanıt sunmaktadır.

Şekil 3. Yoğurt Üzeri Fonksiyonel Toz Duyusal Analiz Sonuçları (9-Puanlı Hedonik Skala, n=15)



3.4. Ürün Kategorilerinin Karşılaştırmalı Değerlendirmesi

Üç model ürünün ortalama genel beğeni puanları karşılaştırıldığında yoğurt topping uygulamasının (7,19) diğer kategorilere belirgin biçimde üstün olduğu görülmektedir. Atıştırmalık bar formülasyonları arasında AB-F1'in (%5) 7,00 puanla optimum düzeyi temsil ettiği, tohum kraker formülasyonlarında ise yalnızca TK-K ve TK-F1'in belirlenen kabul eşiğinin (≥7,0) üzerinde kaldığı anlaşılmaktadır.

Renk koyulaşması ve acılık, yüksek konsantrasyonlarda tüm ürün kategorilerinde ortak bir sınırlayıcı faktör olarak öne çıkmıştır. Bu bulgular, literatürdeki verilerle örtüşmekte; ekmekte %6-10, glutensiz ekmekte %8 ve kurabiyelerde %15-20 dolaylarında gözlenen kritik eşik değerlere paralel bir örüntü sergilemektedir. Çörek otu küspesinin matris tipine göre farklı kabul düzeyleri göstermesi, küspede bulunan fenolik bileşikler ve timokinonun farklı gıda bileşenleriyle olan etkileşim dinamiklerinden kaynaklanabilir (Trigui et al., 2021). Yüksek yağ ve protein içeriğinin, belirli matrislerde acılık algısını azaltabileceği de göz ardı edilmemelidir (Kamandloo et al., 2023).

4. Sonuç ve Öneriler

Bu çalışma, soğuk pres çörek otu küspesinin yoğurt üzeri fonksiyonel un, yulaf–çörek otu atıştırmalık bar ve tohum kraker olmak üzere üç farklı model gıda kategorisinde fonksiyonel bir bileşen olarak kullanılabilirliğini duyusal analiz yöntemiyle ortaya koymaktadır. Yazarların bilgisi dahilinde, soğuk pres çörek otu küspesi bir süt ürünü matrisiyle (yoğurt) ilk kez bu çalışmada birleştirilmiş ve duyusal açıdan değerlendirilmiştir. Yoğurt topping uygulaması üç ürün kategorisi arasında en yüksek kabul edilebilirlik düzeyini sergilemiş; bu bulgu, çörek otu küspesinin süt ürünleriyle anlamlı bir tat uyumu gösterebileceğine işaret etmektedir. Söz konusu uyumun, puding ve benzeri kremalı süt ürünlerine de aktarılabileceği ve bu tür ürünlerin besinsel profilini zenginleştirme potansiyeli taşıdığı değerlendirilmektedir.

Yulaf–çörek otu atıştırmalık barda %5-10, tohum krakerde ise %6 düzeyindeki küspe içerme oranlarının hem kabul edilebilir duyusal profil hem de artırılmış besinsel değer sunduğu ve bu aralıkların ticari açıdan uygulanabilir olduğu değerlendirilmektedir.

Gelecek çalışmalarda, çörek otu küspesinin fermente süt ürünleri başta olmak üzere farklı gıda matrislerindeki kullanım olanaklarının genişletilmesi öncelikli araştırma konuları arasında yer alabilir. Buna ek olarak, acılık maskeleme tekniklerinin (mikrokapsülleme, enzimatik muamele, yağ alma) duyusal profil üzerine etkileri incelenebilir. Tohum kraker formülasyonlarında panelistlerce dile getirilen tuzluluk şikâyetleri göz önünde bulundurulduğunda, tuz oranının azaltılmasının genel beğeniyi olumlu yönde etkileyebileceği öngörülmektedir. Geniş kapsamlı tüketici panelleri ve duyusal haritalama yöntemleri (RATA, CATA) aracılığıyla formülasyon optimizasyonu gerçekleştirilebilir. Öte yandan, küspede bulunan fenolikler ve minerallerden kaynaklanan biyoerişilebilirlik ve fonksiyonel etkinlik boyutlarının derinlemesine araştırılması, bu bileşenin sağlık iddialarına dayalı ürünlerdeki konumlanmasını güçlendirecektir.

Teşekkür

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FUNGİSİT KULLANIMININ İNSAN SAĞLIĞI VE ÇEVRE ÜZERİNDEKİ TOKSİKOLOJİK ETKİLERİ: RİSK DEĞERLENDİRME YÖNTEMLERİ

TOXICOLOGICAL EFFECTS of FUNGICIDE USE on HUMAN HEALTH and ENVIRONMENT: RISK ASSESSMENT METHODS

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ÖZET

Fungal patojenler, küresel tarımsal üretimde önemli verim ve kalite kayıplarına yol açan başlıca biyotik stres faktörlerinden biridir. Bu kayıpların azaltılmasında fungisitler, modern bitki koruma programlarının en önemli pestisitlerinden biri olarak yaygın şekilde kullanılmaktadır. Ancak fungisit kullanımı sonucunda kalıntılarının gıda zincirine taşınması, su kaynaklarına ulaşması ve toprak mikrobiyotasını etkilemesi gibi süreçler aracılığıyla çevresel kirlilik, insan sağlığı riskleri ve hedef dışı organizmalar (Arılar, solucanlar, kuşlar, balıklar vs.) üzerinde olumsuz etkiler oluşturabilmektedir. Bu nedenle fungisitlerin toksikolojik açıdan kapsamlı bir şekilde değerlendirilmesi sürdürülebilir tarım uygulamaları açısından büyük önem taşımaktadır. Fungisitlere uzun süreli maruziyetin insanlarda metabolik ve fizyolojik değişimler sonucu sağlık sorunlarının ortaya çıkmasına (nörotoksisite, endokrin bozucu etkiler gibi), toprak ve su ekosistemlerinde biyolojik dengenin bozulması gibi çeşitli sonuçlara yol açabileceği bildirilmektedir. Bu derlemede fungisitlerin çevresel davranışı, insan sağlığı üzerindeki etkileri ve ekosistem açısından taşıdığı potansiyel riskler güncel literatür çerçevesinde değerlendirilmiştir. Bu kapsamda toprakta kalıcılık, taşınma ve bozunma süreçleri ele alınmış, ayrıca tehlikeyi tanımlama, maruziyeti değerlendirme ve risk faktörlerine dayalı güncel yaklaşımlar incelenmiştir. Elde edilen bilgiler doğrultusunda, fungisit kullanımının sürdürülebilir tarım sistemlerindeki yeri tartışılmış; fungisitlerin risk temelli yaklaşımlar doğrultusunda planlanması ve bitki hastalıkları ile mücadelede entegre mücadele stratejileri ile birlikte ele alınmasının sürdürülebilir tarım ve gıda güvenliği açısından kritik önem taşıdığı vurgulanmıştır.

Anahtar kelimeler: Fungisit toksikolojisi, pestisit kalıntıları, çevresel risk, insan sağlığı

ABSTRACT

Fungal pathogens are one of the most important biotic stress factors leading to significant yield and quality losses in global agricultural production. Fungicides are widely applied as an essential component of modern plant protection programmes to mitigate yield and quality losses caused by fungal diseases. However, the utilization of fungicides has the potential to result in environmental contamination, risks to human health, and deleterious effects on non-target organisms (e.g., bees, earthworms, birds, and fish) through processes such as the transfer of residues into the food chain, contamination of water sources, and disruption of soil microbiota. Consequently, a comprehensive toxicological evaluation of fungicides is imperative for the promotion of sustainable agricultural practices. It has been reported that long-term exposure to fungicides may result in a range of outcomes, including the emergence of health concerns in humans due to metabolic and physiological changes (e.g., neurotoxicity and endocrine-disrupting effects), as well as the disruption of biological equilibrium in soil and aquatic ecosystems. In this review, the environmental behavior of fungicides, their effects on human health, and the potential risks they pose to ecosystems have been assessed within the framework of current literature. In this context, the focus has been on examining persistence, transport, and degradation processes in soil, alongside the current approaches based on hazard identification, exposure assessment, and risk factors. In consideration of the information obtained, the role of fungicide use in sustainable agricultural systems has been discussed. It has been emphasized that the planning of fungicide uses in accordance with risk-based approaches, and its consideration alongside integrated pest management strategies in the control of plant diseases, is of critical importance for sustainable agriculture and food safety.

Key words: Fungicide toxicology, pesticide residues, environmental risk, human health.

1. GİRİŞ

Tarımsal üretimde karşılaşılan en önemli biyotik stres faktörlerinden biri bitki patojenleridir ve özellikle fungal patojenler, dünya genelinde önemli verim ve kalite kayıplarına neden olmaktadır. Bu kayıpların azaltılması amacıyla 80 yılı aşkın bir süredir sentetik pestisitlerin kullanılmaya başlanmasından bu yana üreticiler birim alandan daha fazla verim ve kalite elde etmeyi başarmışlardır (Oerke ve Dehne, 2004). Pestisitler; insektisitler, herbisitler ve fungisitler gibi farklı grupları içermekte olup, bu gruplar arasında fungisitler bitki hastalıklarının kontrolünde kritik bir rol oynamaktadır (FAO, 2024). Fungisitlerin kullanımı sayesinde tarımsal üretimde yüksek verim artışları sağlanmış, soframıza gelen gıda güvence altına alınmış ve ürün kalitesinde iyileşmeler elde edilmiştir (Aktar vd., 2009; Carvalho, 2017; Garud vd., 2024). Artan dünya nüfusu, iklim değişikliği ve tarımsal alanların sınırlı olması gibi faktörler, birim alandan elde edilen verimin artırılmasını zorunlu kılmaktadır. Fungisit kullanımı, yalnızca bitki hastalıklarının kontrolü açısından değil, aynı zamanda gıda güvenliğinin sağlanması açısından da stratejik bir öneme sahiptir. Bununla birlikte, Pestisitlerin ve özellikle fungisitlerin yaygın kullanımı, çevrede kalıntı ve ekosistem üzerinde olumsuz etkiler oluşturabilmektedir (Pathak vd., 2022; Zhou vd., 2024). Bitki hastalıkları ile mücadelede kullanılan fungisitler, tarım alanlarından ve meyve-sebze işleme tesislerinden gelen akıntı yoluyla toprak, yeraltı suyu ve yüzeyleri kirletme potansiyeline sahiptir. Toprak, meyve ve sebzeler, içme suyu, belediye kanalizasyonu, yeraltı suyu ve kanalizasyon atık çamuru dahil olmak üzere çevre açısından ciddi kirleticiler haline gelmişlerdir.

Fungisitler ve bunların parçalanma ürünleri, insan sağlığı ile sucul ve karasal ekosistemlerde yaşayan diğer canlılar açısından potansiyel riskler oluşturabilmektedir (Wronski vd., 2024). Tarımsal uygulamalar sonrasında bu kimyasalların yalnızca bir bölümü hedef organizmalar üzerinde etkili olurken, önemli bir kısmı çevreye yayılmaktadır. Özellikle yüzey akışı, yeraltı suyu taşınımı ve atmosferik taşınım gibi süreçler, fungisitlerin toprak, su ve hava ortamlarındaki dağılımında belirleyici rol oynamaktadır (Juksu vd., 2019; Carvalho, 2017; Pathak vd., 2022). Çevreye taşınan bu kalıntılar, birçok canlı üzerinde toksik etkilere neden olarak biyolojik çeşitliliğin azalmasına, ekosistemin bozulmasına ve besin zincirinde birikime yol açabilmektedir (Aktar vd., 2009; Zhang vd., 2020; Pimentão vd., 2024). Örneğin, bitkilere uygulanan bakırlı preparatlar, sucul mikroorganizmaların evrimsel süreçlerini etkileyerek metal toleranslı mikroorganizmaların ortaya çıkmasına neden olabilmektedir (Islam, 2017).

İnsan sağlığı açısından değerlendirildiğinde, fungisitlere maruziyetin farklı yollarla gerçekleştiği bilinmektedir. Bunlar arasında en yaygın maruziyet yolları; kontamine gıdaların tüketimi, içme suyu yoluyla alım, solunum ve dermal temas olarak sıralanabilir. Bu maruziyet yolları, özellikle tarım işçileri, kırsal bölgelerde yaşayan bireyler ve hassas gruplar açısından daha yüksek risk oluşturmaktadır. Yapılan çalışmalar, fungisit maruziyeti ile çeşitli sağlık sorunları arasında güçlü ilişkiler bulunduğunu ortaya koymuştur. Bu sağlık sorunları arasında nörolojik hastalıklar, endokrin sistem bozuklukları, kanser ve üreme sistemi problemleri yer almaktadır (Kim vd., 2017; Mostafalou & Abdollahi, 2013; Rodrigues vd., 2024; Shekhar vd., 2024). Fungisitlerin insan sağlığı üzerindeki etkileri yalnızca akut zehirlenmeler ile sınırlı değildir. Uzun süreli ve düşük doz maruziyetler, hücresel düzeyde oksidatif stres, genetik hasar ve epigenetik değişiklikler gibi mekanizmalar üzerinden kronik hastalıkların gelişimine katkıda bulunabilmektedir. Ayrıca çocuklar, yaşlılar ve bağışıklık sistemi zayıf bireyler gibi hassas gruplar, daha duyarlı olup, bu gruplarda daha ciddi sağlık etkileri gözlenebilmektedir (Costa vd., 2008; Mostafalou & Abdollahi, 2013; Rodrigues vd., 2024). Son yıllarda yapılan çalışmalar, fungisit kalıntılarının tarımsal ürünlerde, su kaynaklarında ve hatta insan biyolojik örneklerinde tespit edilebildiğini ortaya koymaktadır. Özellikle strobilurin grubu fungisitlerin çevresel ortamlarda yaygın olarak bulunması ve düşük konsantrasyonlarda dahi biyolojik

etkiler oluşturabilmesi, bu bileşiklerin risk değerlendirme açısından önemini artırmaktadır (Leite vd., 2024; Liu vd., 2025; Sokołowska vd., 2025).

Fungisitlerin çevre ve insan sağlığı üzerine toksikolojik etkileri, risk değerlendirme yaklaşımlarının önemini artırmaktadır. Uluslararası düzeyde kabul gören risk değerlendirme modelleri, Fungisitlerin güvenli kullanımının sağlanması ve olası zararlarının minimize edilmesi açısından temel bir araç olarak kullanılmaktadır. Bu modeller, tehlikeyi tanımlama, maruziyet değerlendirmesi ve risk durumu gibi aşamaları içermekte olup, fungisitlerin insan ve çevre üzerindeki etkilerinin bilimsel temelde değerlendirilmesine olanak sağlamaktadır. Fungisitlerin toksikolojik değerlendirilmesi, Avrupa Birliği'nde Regulation (EC) No 1107/2009 kapsamında yürütülen ruhsatlandırma süreçlerinde insan sağlığı, çevresel güvenlik ve gıda zinciri üzerindeki etkilerin bütüncül olarak ele alındığı çok aşamalı bir risk değerlendirme sistemine dayanmaktadır (European Commission, 2009; EFSA, 2013; FAO/WHO, 2023; US EPA, 2022). Bu doğrultuda, entegre mücadele (IPM), biyolojik mücadele yöntemleri ve düşük riskli fungisitlerin kullanımı gibi alternatif stratejiler ön plana çıkmaktadır. Ayrıca fungisit kullanımının azaltılarak çevresel etkilerinin azaltılabilmesi amacıyla mikroorganizmalar (fungus, bakteri, alg) veya bitkiler kullanılarak (biyoremediasyon) çevre kirliliğinin azaltılması ile çevre dostu yöntemler de önem kazanmaktadır (Pathak vd., 2022; Zhou vd., 2024; Muñoz-Bautista vd., 2025).

Sonuç olarak, fungisitler tarımsal üretimde önemli derecede faydalar sağlamakla birlikte, insan sağlığı ve çevre üzerinde oluşturabilecekleri olumsuz etkiler nedeniyle dikkatli ve kontrollü şekilde kullanılmalıdır. Bu nedenle, fungisit kullanımının risk temelli yaklaşımlar doğrultusunda değerlendirilmesi ve sürdürülebilir tarım sistemleri ile entegre edilmesi büyük önem taşımaktadır. Bu derleme; yaygın ve yoğun kullanımı nedeniyle çevresel ve toksikolojik açıdan giderek daha fazla önem kazanan fungisitlerin, güncel literatür çerçevesinde kapsamlı biçimde değerlendirilmesi amacıyla hazırlanmıştır. Derlemede üç temel kısım ele alınmıştır: (1) fungisitlerin toprakta kalıcılığını, taşınmasını ve parçalanma süreçlerini kapsayan çevresel davranışı ve ekosistem açısından taşıdığı potansiyel riskler; (2) fungisite maruziyet yolları ile akut ve kronik toksisite aracılığıyla ortaya çıkan insan sağlığı üzerindeki etkileri; (3) tehlikeyi tanımlama, maruziyet değerlendirmesi ve risk durumunu içeren uluslararası risk değerlendirme yaklaşımları. Elde edilen bulgular doğrultusunda, fungisit kullanımının risk temelli yaklaşımlar ve entegre mücadele (IPM) stratejileri çerçevesinde planlanmasının sürdürülebilir tarım ve gıda güvenliği açısından kritik önem taşıdığı vurgulanmıştır.

2.FUNGİSİTLERİN ÇEVRESEL DAVRANIŞI VE EKOTOKSİKOLOJİSİ

2.1 Çevresel Durum ve Toprakta Kalıcılık

Fungisitlerin çevresel davranışı; uygulama sonrası maruz kaldıkları fiziksel, kimyasal ve biyolojik süreçlerin bir sonucu olarak şekillenmektedir. Bu süreçler genel olarak adsorpsiyon, desorpsiyon, taşınma, dönüşüm ve parçalanma mekanizmalarını içermektedir. Fungisitlerin bu süreçlerdeki davranışı, molekülün kimyasal yapısına, çevresel koşullara ve uygulama yöntemine bağlı olarak değişmektedir (Pathak vd., 2022; Liu vd., 2025). Toprak ortamında fungisitlerin önemli bir kısmı organik maddeye bağlanarak tutulmakta, ancak düşük adsorpsiyon kapasitesine sahip bileşikler kolaylıkla yeraltı sularına taşınabilmektedir. Özellikle yağış ve sulama sonrası oluşan yüzey akışı, fungisitlerin tarım alanlarından uzaklaşarak sucul ekosistemlere ulaşmasında kritik rol oynamaktadır. Bu durum, fungisitlerin yalnızca uygulandıkları alanlarda değil, daha geniş coğrafi bölgelerde de tespit edilmesine yol açmaktadır (Carvalho, 2017; Pimentão vd., 2024; Sokołowska vd., 2025). Fungisitlerin çevredeki kalıcılığı, yarı ömür (DT_{50}) değerleri ile ifade edilmekte olup, bazı fungisitlerin

toprakta ve suda uzun süre stabil kalabildiği bilinmektedir. Özellikle strobilurin ve azol grubu fungisitler, çevrede kalıcı olabilen ve metabolitleri ile birlikte uzun süreli etki gösterebilen bileşikler arasında yer almaktadır. Özellikle azol grubu fungisitlerin, canlılarda hormonal dengede bozulmalara ve sucul organizmaların üreme ve fizyolojik sistemleri üzerinde olumsuz etkilere yol açtığı belirtilmiştir (Juksu vd., 2019). Bu durum, kronik maruziyet riskini artırmakta ve çevresel risk değerlendirmesini daha karmaşık hale getirmektedir (Leite vd., 2024; Liu vd., 2025; Zhang vd., 2020). Fungisitlerin biyotik dönüşüm süreçleri, mikroorganizmalar tarafından gerçekleştirilen biyodegradasyon mekanizmaları ile yakından ilişkilidir. Ancak bazı durumlarda bu dönüşüm ürünleri, ana bileşikten daha toksik olabilmektedir. Bu nedenle yalnızca aktif madde değil, parçalanma ürünlerinin de risk değerlendirme süreçlerine dahil edilmiştir (Liu vd., 2025; Pathak vd., 2022).

2.2. Çevreye Dağılım: Kalıntılar, Biyobirikim ve Biyomagnifikasyon

Fungisit kalıntıları, günümüzde en önemli çevresel ve gıda güvenliği problemlerinden biri olarak değerlendirilmektedir. Tarımsal uygulamalar sonrasında ürün yüzeyinde kalan kalıntılar, hasat sonrası tüketim yoluyla doğrudan insan vücuduna alınabilmektedir. Bunun yanı sıra fungisitler; su kaynakları, toprak ve atmosferik taşınım yoluyla geniş alanlara yayılabilmektedir (Carvalho, 2017; Zhou vd., 2024). Çalışmalar, fungisit kalıntılarının yalnızca tarım ürünlerinde değil, içme sularında, yüzey sularında ve hatta insan biyolojik örneklerinde (idrar, kan) dahi tespit edilebildiğini göstermektedir. Bu durum, fungisit maruziyetinin düşündüğümüzden daha yaygın ve sürekli olduğunu ortaya koymaktadır. Fungisitlerin çevresel yayılımında başlıca faktörlerden biri de biyobirikim ve biyomagnifikasyon süreçleridir. Lipofilik özellik gösteren fungisitler, organizmaların yağ dokularında birikerek trofik seviyeler boyunca taşınabilmekte ve üst trofik düzeylerde daha yüksek konsantrasyonlara ulaşabilmektedir. Bu durum özellikle balıklar ve sucul organizmalar açısından büyük önem taşımaktadır (Leite vd., 2024; Zhou vd., 2024; Sokołowska vd., 2025; Liu vd., 2025). Ayrıca atmosferik taşınım yoluyla fungisitlerin uzak bölgelere taşınması, bu kimyasalların küresel ölçekte yayılım gösterebildiğini ortaya koymaktadır. Bu durum, fungisitlerin yalnızca yerel değil, aynı zamanda bölgesel ve küresel çevresel riskler oluşturduğunu göstermektedir (Carvalho, 2017; Pimentão vd., 2024).

2.3. Ekosisteme Etkiler: Sucul ve Karasal Organizmalar

Fungisitlerin ekotoksikolojik etkileri, sucul ve karasal ekosistemlerde farklı şekillerde ortaya çıkmaktadır. Sucul ekosistemler, fungisit kirliliğine karşı en hassas sistemlerden biri olarak kabul edilmektedir. Bunun temel nedeni, fungisitlerin su ortamında daha kolay taşınması ve organizmaların doğrudan maruziyetine açık olmasıdır (Pimentão vd., 2024; Zhang vd., 2020). Suda çözünür fungisitler, göller, nehirler ve yeraltı sularında birikerek balıklar, algler ve planktonlar üzerinde toksik etkiler oluşturabilmektedir. Özellikle strobilurin grubu fungisitlerin mitokondriyal solunum zincirini inhibe ederek enerji üretimini engellediği ve oksidatif stres oluşturduğu gösterilmiştir. Bu mekanizma, organizmaların büyüme, gelişme ve üreme süreçlerini olumsuz etkilemektedir (Leite vd., 2024; Liu vd., 2025).

Karasal ekosistemlerde ise fungisitler, toprak mikroorganizmaları ve omurgasızlar üzerinde önemli etkiler oluşturmaktadır. Toprak mikrobiyotasının yapısının değişmesi, besin döngülerinin bozulmasına ve toprak verimliliğinin azalmasına yol açabilmektedir. Ayrıca solucanlar ve diğer toprak organizmaları üzerinde görülen toksik etkiler, ekosistem fonksiyonlarını doğrudan etkilemektedir (Pathak vd., 2022; Zhou vd., 2024). Polinatörler üzerinde fungisitlerin doğrudan öldürücü etkileri genellikle düşük olmakla birlikte, subletal etkiler, davranış değişiklikleri ve fizyolojik bozulmalar gibi sonuçlar doğurabilmektedir. Bu

durum, tarımsal üretim açısından da dolaylı riskler oluşturmaktadır (Pimentão vd., 2024; Zhang vd., 2020).

3. İNSAN SAĞLIĞI ÜZERİNE TOKSİKOLOJİK ETKİLER

3.1. Maruziyet Yolları, Hassas Gruplar ve Risk Faktörleri

Fungisitlere maruziyet, farklı yollarla gerçekleşebilmektedir. Bunlar arasında en yaygın olanları oral maruziyet (gıda ve su tüketimi), inhalasyon (spreyleme sırasında) ve dermal temastır (Kim vd., 2017; Shekhar vd., 2024). Tarım işçileri, fungisit uygulayıcıları ve kırsal bölgelerde yaşayan bireyler en yüksek maruziyet grubunu oluştururken; çocuklar, yaşlılar ve hamile bireyler gibi hassas gruplar daha düşük dozlarda dahi daha büyük risk altındadır. Özellikle çocuklarda gelişimsel süreçlerin devam ediyor olması, fungisitlere karşı duyarlılığı artırmaktadır (Rodrigues vd., 2024; Shekhar vd., 2024).

3.2 Akut ve Kronik Toksisite: Klinik Bulgular ve Epidemiyolojik Veriler

Fungisitlerin toksik etkileri, maruziyet süresine ve dozuna bağlı olarak akut ve kronik olmak üzere iki temel grupta incelenmektedir.

Akut maruziyet, genellikle yüksek doz ve kısa süreli temas sonucunda ortaya çıkmakta olup klinik bulgular maruziyet yoluna göre farklılık göstermektedir. Dermal temas durumunda deri irritasyonu, kızarıklık ve kontakt dermatit; göz maruziyetinde konjunktivit ve kornea hasarı gözlemlenebilmektedir. Soluma yoluyla gerçekleşen akut maruziyetlerde ise üst solunum yolu irritasyonu, öksürük gibi solunum sistemi bulguları ön plana çıkmaktadır. Baş dönmesi, bulantı, kusma, baş ağrısı ve genel halsizlik de sık bildirilen akut bulgular arasında yer almaktadır (Kim vd., 2017; Garud vd., 2024; Shekhar vd., 2024). Pathak vd. (2022), tarım işçilerinde spreyleme dönemlerinde akut zehirlenme vakalarının belirgin biçimde arttığını ve bu vakaların büyük çoğunluğunun kişisel koruyucu ekipman kullanımındaki yetersizliklerle doğrudan ilişkili olduğunu vurgulamaktadır. Akut etkilerin şiddeti, kullanılan fungisitin kimyasal sınıfına, uygulama dozuna ve bireyin genel sağlık durumuna bağlı olarak önemli ölçüde değişkenlik göstermektedir (Zhou vd., 2024).

Kronik maruziyet, düşük dozda ve uzun süreye yayılan temas sonucunda gelişmekte olup etkileri çoğunlukla sinsi bir seyir izleyerek yıllar sonra klinik olarak kendini göstermektedir. Bu nedenle kronik toksisite, akut etkilerle karşılaştırıldığında epidemiyolojik düzeyde saptanması çok daha güç olmakla birlikte halk sağlığı açısından çok daha ağır sonuçlar doğurabilmektedir (Mostafalou & Abdollahi, 2013; Shekhar vd., 2024). Kronik etkiler arasında en ciddi bulgular nörodejeneratif hastalıklar, endokrin sistem bozuklukları, kanser ve üreme sistemi problemleri olarak öne çıkmaktadır (Kim vd., 2017; Garud vd., 2024). Nörolojik etkiler bu kapsamda özellikle dikkat çekmektedir. Epidemiyolojik çalışmalar, uzun süreli fungisit maruziyeti ile Parkinson hastalığı arasında tutarlı bir ilişki bulunduğunu ortaya koymakta; tarım işçileri ve kırsal bölge sakinlerinde Parkinson hastalığının genel popülasyona kıyasla belirgin düzeyde yüksek olduğu bildirilmektedir. Alzheimer hastalığı başta olmak üzere diğer nörodejeneratif tablolarla fungisit maruziyeti arasındaki ilişki de benzer çalışmalarla desteklenmektedir (Costa vd., 2008; Mostafalou & Abdollahi, 2013). Costa vd. (2008), bu nörotoksik etkilerin büyük ölçüde mitokondriyal disfonksiyon, oksidatif stres ve nöroinflasyon mekanizmaları üzerinden geliştiğini göstermektedir. Endokrin sistem üzerindeki kronik etkiler de epidemiyolojik açıdan önemli bir endişe kaynağı oluşturmaktadır. Fungisitlerin bir bölümünün östrojen reseptörlerini taklit ettiği ya da androjen biyosentezini baskıladığı gösterilmiş; bu mekanizmaların üreme sistemi bozuklukları, tiroid fonksiyon değişiklikleri ve

gelişimsel anomalilerle ilişkilendirilebileceği ileri sürülmüştür (Mostafalou & Abdollahi, 2013; Rodrigues vd., 2024). Özellikle içme suyu yoluyla gerçekleşen kronik düşük doz maruziyet senaryolarında, strobilurin ve azol grubu fungisitlerin endokrin sistemde kalıcı işlev bozukluklarına zemin hazırlayabileceği in vitro çalışmalarla desteklenmektedir (Sokołowska vd., 2025). Kanser riski açısından değerlendirildiğinde, epidemiyolojik veriler fungisit maruziyeti ile lenfoma, lösemi ve prostat kanseri arasında tekrarlayan ilişkiler olduğunu göstermektedir. Leite vd. (2024), strobilurin grubuna özgü kronik toksisite profilinin hücresel düzeyde DNA hasarı ve oksidatif stres yoluyla kanser patogenezine katkıda bulunduğunu bildirmektedir. Benzer şekilde Liu vd. (2025), düşük doz strobilurin maruziyetinin uzun vadede genotoksik potansiyel taşıdığını ve bu nedenle kronik maruziyet sınır değerlerinin yeniden değerlendirilmesi gerektiğini ortaya koymaktadır. Üreme sağlığı üzerindeki etkiler de kronik toksisite kapsamında giderek daha fazla araştırılan bir alan haline gelmektedir. Uzun süreli fungisit maruziyetinin sperm kalitesinde bozulma, ovulasyon düzensizlikleri ve gebelik komplikasyonlarıyla ilişkili olduğu çeşitli çalışmalarla raporlanmıştır. Çocuklar ve hamile bireyler gibi hassas gruplarda bu etkilerin çok daha düşük maruziyet dozlarında dahi ortaya çıkabildiği bildirilmektedir (Rodrigues vd., 2024; Shekhar vd., 2024). Tsalidis (2022), yaşam döngüsü analizine dayalı çalışmasında fungisit kullanımının azaltılmasının yalnızca çevresel değil, aynı zamanda insan sağlığı üzerindeki kronik yük açısından da ölçülebilir iyileşmeler sağlayabileceğini sayısal verilerle ortaya koymuştur. Tüm bu bulgular bir arada değerlendirildiğinde, fungisitlerin yalnızca akut toksik etkileriyle değil, uzun vadeli kronik sonuçları ve epidemiyolojik boyutlarıyla da kapsamlı biçimde ele alınması gerektiği açıkça ortaya çıkmaktadır (Mostafalou & Abdollahi, 2013; Zhou vd., 2024).

3.3. Fungisitlerin Biyokimyasal Etki Mekanizmaları

Fungisitlerin insan ve çevre sağlığı üzerindeki toksik etkileri, birbirinden farklı ancak çoğu zaman birbirini besleyen dört temel biyokimyasal mekanizma üzerinden ortaya çıkmaktadır: oksidatif stres, endokrin sisteminin bozulması, genotoksisite ve mitokondriyal işlev bozukluğu. Bu mekanizmaların düşük doz maruziyetlerde dahi devreye girebilmesi, kronik sağlık risklerinin değerlendirilmesi açısından özel bir önem taşımaktadır. Fungisitlere maruziyetin en yaygın ve temel biyokimyasal sonuçlarından biri, hücre içinde reaktif oksijen türlerinin aşırı birikmesiyle ortaya çıkan oksidatif strestir. Bu durum, hücrenin doğal antioksidan savunma kapasitesini aşarak zar yapısında, proteinlerde ve genetik materyalde kalıcı hasara yol açmaktadır (Costa vd., 2008; Mostafalou & Abdollahi, 2013). Azol grubuna ait tebukonazolün insan kalp kası hücrelerinde oksidatif hasar belirteçlerini belirgin biçimde artırdığı ve hücre ölüm süreçlerini tetiklediği in vitro çalışmalarla ortaya konmuştur (Sokołowska vd., 2025). Strobilurin grubundan azoksistrobinin ise çevresel düzeylerde bile canlı dokularda antioksidan enzim dengesini bozduğu ve oksidatif hasar belirteçlerini yükselttiği gösterilmiştir (Leite vd., 2024; Liu vd., 2025). Fungisitlerin, hücreleri serbest radikallere karşı koruyan enzimlerin işlevini baskılaması, farklı organ sistemlerinde kümülatif bir hasara zemin hazırlamaktadır (Pathak vd., 2022). Fungisitlerin hormon sistemi üzerindeki etkileri de son yıllarda giderek daha fazla araştırılan bir alan haline gelmiştir. Azol ve triazol grubu fungisitler, fungus hücrelerini hedef alırken memelilerde de steroid hormon üretimini düzenleyen enzim sistemlerini etkileyerek hormonal dengeyi bozabilmektedir (Carlier vd., 2024). Özellikle östrojen biyosentezinde kilit rol oynayan aromataz enziminin bu bileşikler tarafından baskılanması, cinsiyet hormonu dengesini önemli ölçüde sekteye uğratmaktadır (Rodrigues vd., 2024). Tebukonazol ve siprokonazol gibi yaygın triazollerin androjen ve östrojen düzeylerini düşürdüğü çalışmalarla doğrulanmış; gebelik dönemindeki maruziyet bağlamında bu tablonun üreme sistemi gelişim bozuklukları açısından ciddi riskler taşıdığı vurgulanmıştır (Carlier vd., 2024; Rodrigues vd., 2024; Sokołowska vd., 2025). Fungisitlerin genetik materyal üzerindeki

olumsuz etkileri, hem doğrudan DNA kırıklarına hem de reaktif oksijen türleri aracılığıyla gerçekleşen dolaylı hasara dayanmaktadır. Çeşitli araştırmalar, strobilurin ve triazol grubuna ait fungisitlerin hayvan ve insan hücrelerinde doza bağımlı genetik hasara neden olduğunu ortaya koymaktadır (Liu vd., 2025). Tebukonazolün, hücre zehirliliği oluşturmayan konsantrasyonlarda dahi insan hücrelerinde DNA bütünlüğünü bozduğu bildirilmektedir (Leite vd., 2024). Triazol ve strobilurin içeren ticari karışımların tek başına kullanılan bileşenlere kıyasla çok daha belirgin genetik hasar oluşturduğu da dikkat çeken bulgular arasındadır; bu durum, karışım toksisitesinin risk değerlendirmelerinde ayrıca ele alınması gerektiğini açıkça ortaya koymaktadır (Liu vd., 2025). Uzun süreli düşük doz maruziyette gözlemlenen bu genotoksik potansiyelin kanser gelişimine zemin hazırlayabileceği değerlendirilmekte ve mevcut güvenlik eşiklerinin yeniden gözden geçirilmesi gerektiği vurgulanmaktadır (Leite vd., 2024; Liu vd., 2025). Fungisitlerin, özellikle strobilurin sınıfının, hücrenin enerji üretim merkezi olan mitokondrinin çalışmasını köklü biçimde sekteye uğrattığı bilinmektedir (Liu vd., 2025). Fungus hücrelerini hedef almak amacıyla geliştirilen bu etki mekanizması, memelilerin hücresel yapısı üzerinde de benzer sonuçlar doğurabilmektedir. İnsan karaciğer hücreleri üzerinde yürütülen çalışmalar, piraklostrobin maruziyetinin enerji üretimini ve hücresel antioksidan kapasiteyi anlamlı ölçüde düşürdüğünü, buna karşın zararlı oksijen radikali üretimini artırdığını göstermektedir. Farklı strobilurin türlerinin birlikte kullanıldığı durumlarda, her birinin ayrı ayrı toksik olmayan dozlarında dahi belirgin hücresel hasar oluştuğu gözlemlenmiş; bu sinerjistik etki, kombinasyon risklerinin ayrıca değerlendirilmesi gerektiğini ortaya koymuştur (Carbone vd., 2023). Söz konusu işlev bozukluğunun aynı zamanda sinir sistemi gelişimi sırasındaki hücre göçünü sekteye uğratabileceğine dair bulgular, gelişimsel toksikoloji açısından yeni kaygılar doğurmaktadır (Magel vd., 2024). Enerji üretimindeki bu düşüş, hücre ölüm mekanizmalarıyla birleşerek karaciğer, böbrek ve sinir sistemi gibi yüksek enerji talebine sahip dokularda kalıcı hasara zemin hazırlamaktadır (Costa vd., 2008; Leite vd., 2024).

4. RİSK DEĞERLENDİRME

4.1. Risk Değerlendirme Metodolojisi: Tehlike Tanımlama, Maruziyet ve Risk

Fungisitlerin güvenli kullanımının sağlanabilmesi için risk değerlendirme süreçleri uluslararası düzeyde standartlaştırılmıştır. Bu süreçler üç temel aşamadan oluşmaktadır: tehlike tanımlama, maruziyet değerlendirmesi ve risk değerlendirme. Bu yaklaşım, fungisitlerin insan sağlığı ve çevre üzerindeki etkilerinin bilimsel olarak değerlendirilmesini sağlamaktadır. Risk değerlendirme aşaması, toksisite ve maruziyet verilerinin birlikte değerlendirilmesi ile gerçek riskin ortaya konduğu en kritik aşama olarak kabul edilmektedir (EFSA, 2013; FAO/WHO, 2023; US EPA, 2022).

4.2. Uluslararası Sistem: FAO, WHO, EFSA ve EPA Yaklaşımları

Fungisitlerin güvenli kullanımının sağlanması, uluslararası kuruluşlar tarafından geliştirilen bilimsel değerlendirme sistemlerine dayanmaktadır. Bu sistemler, yöntem ve öncelikler bakımından birbirinden farklılık gösterse de hepsinin ortak hedefi fungisit kalıntılarının insan sağlığı ve çevre üzerindeki olumsuz etkilerini bilimsel temelde ortaya koymak ve bu riskleri yönetilebilir düzeyde tutmaktır. Küresel ölçekte en kapsamlı pestisit kalıntı değerlendirme sistemi, FAO ve WHO tarafından ortaklaşa yürütülen Pestisit Kalıntıları Ortak Toplantısı'dır (JMPR). 2023 yılında Washington'da gerçekleştirilen toplantıda 35 pestisit incelenmiş; uluslararası gıda standartları çerçevesinde ülkelerin başvurabileceği maksimum kalıntı sınır değerleri belirlenmiş ve bu değerlerin günlük gıda tüketimi sırasında aşılıp aşılmadığı da ayrıca değerlendirilmiştir (FAO/WHO, 2023). JMPR, yalnızca tek bir kimyasalın etkisini değil; farklı

gıda yollarıyla biriken toplam maruziyeti, çocuklar ve hamile bireyler gibi özellikle duyarlı grupları ve yüksek tüketim alışkanlıklarına sahip bireyleri de kapsayan geniş bir perspektifle çalışmaktadır. Bu özelliği, sistemi küresel bir referans noktası hâline getirmektedir. Avrupa Birliği'nde fungisit değerlendirme süreçleri, Avrupa Gıda Güvenliği Otoritesi (EFSA) koordinasyonunda ve üye devletlerle iş birliği içinde yürütülmektedir. Bu sürecin yasal dayanağını oluşturan Regulation (EC) No 1107/2009, bitki koruma ürünlerinin piyasaya sürülmesi, kullanımı ve denetlenmesine ilişkin kapsamlı kurallar belirlemekte; hem insan ve hayvan sağlığının hem de çevrenin üst düzeyde korunmasını temel ilke olarak benimsemektedir (European Commission, 2009). Yönetmelik, güçlü bir ihtiyatlılık anlayışına dayanmakta; bilimsel belirsizlik durumlarında yetkili otoritelerin bu ilkeyi uygulamasının önünde hiçbir engel bulunmaması gerektiğini açıkça ortaya koymaktadır. Buna göre bir aktif maddenin insan sağlığı, hayvan sağlığı ve çevre üzerinde herhangi bir zararlı etki oluşturmadığı kanıtlanmadan piyasaya sürülmesine izin verilmemektedir. Onaylanan aktif maddeler en fazla 10 yıllık sürelerle sınırlandırılmakta ve bu sürenin sonunda yenileme başvurusu yapılması zorunlu tutulmaktadır. Yönetmelik ayrıca hamile kadınlar, bebekler, çocuklar ve yaşlılar gibi hassas gruplarının korunmasına özellikle dikkat çekmekte; bu gruplar için maruziyet değerlendirmelerinde ek güvenlik önlemlerinin gözetilmesini zorunlu kılmaktadır. Bu çerçevede fungisitlerin insan sağlığına, çevreye ve gıda zincirine olası etkileri bütüncül bir bakış açısıyla ele alınmaktadır (European Commission, 2009; EFSA, 2013). Amerika Birleşik Devletleri'nde ise Çevre Koruma Ajansı (EPA), pestisit değerlendirmesinde daha dengeci bir tutum sergilemektedir. EPA, bir fungisitin tarımsal açıdan sağladığı faydayı insan sağlığı ve çevre üzerindeki olası olumsuz etkilerle birlikte ele alarak her iki tarafı da gözeten bir değerlendirme anlayışı benimsemiştir. Piyasaya çıkan pestisitler her 15 yılda bir bu çerçevede yeniden incelenmekte; güncel bilimsel bulgular ışığında güvenlik standartlarının sürdürülüp sürdürülmediği denetlenmektedir (US EPA, 2022). EPA ayrıca pestisit kararlarının bilimsel gerekçelerini kamuoyuyla şeffaf bir biçimde paylaşmakta ve risk değerlendirme süreçlerine halk katılımına açık bir yapı sunmaktadır. Söz konusu sistemlerin karşılaştırmalı olarak değerlendirilmesi, fungisit yönetimindeki öncelik farklılıklarını açıkça yansıtmaktadır. JMPR küresel bir referans çerçevesi sunarken, EFSA çevresel sürdürülebilirliği ve tüketici güvenliğini ön planda tutan korumacı bir anlayışla hareket etmekte; EPA ise bilimsel şeffaflığı ve yarar-zarar dengesini birlikte gözeten pragmatik bir çizgide ilerlemektedir. Güncel araştırmalar, bu sistemlerin farklı kimyasalların birlikte yarattığı etkiler, uzun süreli düşük doz maruziyetin kronik sonuçları ve hassas gruplar üzerindeki özel riskler konularında daha bütünleşik ve dinamik bir yapıya kavuşturulması gerektiğini vurgulamaktadır (FAO/WHO, 2023; Liu vd., 2025; Shekhar vd., 2024).

4.3. Risk Yönetimi Stratejileri ve Sürdürülebilir Alternatifler

Fungisit kullanımından kaynaklanan çevresel ve sağlık risklerinin yönetilmesi, yalnızca kimyasal kullanımı kısıtlamakla değil, aynı zamanda etkili alternatif stratejilerin devreye sokulmasıyla mümkün olmaktadır. Bu kapsamda en köklü ve bilimsel temelli yaklaşım, kimyasal mücadeleyi biyolojik, kültürel ve mekanik yöntemlerle bir arada ele alan entegre mücadeledir (IPM). IPM uygulamaları, fungisit kullanım miktarını önemli ölçüde azaltırken hastalık kontrolündeki etkinliği korumakta; böylece hem çevresel yük hem de insan sağlığına yönelik maruziyet riski eş zamanlı olarak düşürülmektedir (Zhou vd., 2024). Hassas tarım uygulamaları da sürdürülebilir fungisit yönetiminde belirleyici bir rol üstlenmektedir. Hastalık odaklarının erken ve doğru tespit edilmesine dayanan bu yaklaşım, fungisitin yalnızca gerçekten gerekli olan alanlarda ve optimum dozda uygulanmasını sağlamakta; bu sayede tarım alanlarından su kaynaklarına ve toprağa taşınan kimyasal yükü önemli ölçüde sınırlandırmaktadır (Pimentão vd., 2024).

Biyolojik mücadele ve mikroorganizma temelli biyofungisitler, kimyasal fungisitlere karşı sürdürülebilir bir alternatif olarak öne çıkmaktadır. Patojen popülasyonlarını baskılayan bu biyolojik etkenler, ekosistem dengesini korurken kimyasal kalıntı oluşumunu da en aza indirmektedir. Yaşam döngüsü analizine dayalı çalışmalar, fungisit kullanımının azaltılmasının özellikle meyve ve sebze üretiminde insan sağlığı ve ekosistem kalitesi üzerinde ölçülebilir iyileşmeler sağladığını ortaya koymaktadır (Tsalidis, 2022).

Fungisit kalıntılarının çevreden uzaklaştırılması açısından ise mikroorganizma temelli parçalanma süreçleri, bitkiler aracılığıyla gerçekleştirilen temizleme uygulamaları ve ileri oksidasyon yöntemleri etkili ve çevre dostu seçenekler olarak değerlendirilmektedir (Pathak vd., 2022; Zhou vd., 2024). Son yıllarda nanoteknoloji tabanlı yaklaşımlar bu alanda yeni bir perspektif sunmaktadır. Kontrollü salım özelliğine sahip nanopestisitler, aktif maddenin hedefe daha etkin biçimde ulaşmasını sağlayarak kullanılan toplam miktarı ve çevresel yayılımı azaltmaktadır. Nanobiyosensör teknolojileri ise fungisit kalıntılarının gerçek zamanlı izlenmesine olanak tanıyarak risk yönetimi süreçlerini güçlendirmektedir (Muñoz-Bautista vd., 2025). Bununla birlikte, mevcut fungisit kullanım düzeylerinin ekolojik sürdürülebilirlik hedefleriyle tam uyumlu olmadığı ve kullanım verileriyle ekotoksikolojik değerlendirmeler arasında önemli boşluklar bulunduğu bildirilmektedir (Pimentão vd., 2024). Bu nedenle bölgesel koşulları ve gerçek kullanım örüntülerini yansıtan risk değerlendirme yaklaşımlarının geliştirilmesi, sürdürülebilir fungisit yönetiminde öncelikli bir gereklilik olarak öne çıkmaktadır.

Sonuç olarak, fungisit kullanımının sürdürülebilirliği; kimyasal girdilerin azaltılması, alternatif mücadele yöntemlerinin yaygınlaştırılması, ileri teknolojilerin kullanımı ve uluslararası risk değerlendirme çerçeveleri ile uyumlu etkin yönetim stratejilerinin birlikte uygulanmasına bağlıdır. Bu bütüncül yaklaşım, tarımsal üretimin devamlılığını sağlarken insan sağlığı ve çevresel sürdürülebilirlik açısından kritik bir denge oluşturmaktadır.

5. SONUÇ VE ÖNERİLER

5.1. Genel Değerlendirme

Bu derleme kapsamında ele alınan bulgular, fungisitlerin tarımsal üretimdeki vazgeçilmez rolünün yanı sıra insan sağlığı ve ekosistemler üzerinde yarattığı riskleri bir bütün olarak ortaya koymaktadır. Fungisitlerin toprak, su ve atmosfer ortamlarında taşınabilmesi, sucul ve karasal ekosistemlerde kalıcı izler bırakması ve besin zinciri boyunca birikme potansiyeli taşıması, bu kimyasalların çevresel etkilerinin yalnızca uygulama alanıyla sınırlı kalmadığını açıkça göstermektedir. İnsan sağlığı açısından değerlendirildiğinde ise uzun süreli düşük doz maruziyetin; hücresel düzeyde oksidatif hasar, hormonal denge bozukluğu ve genetik hasar gibi mekanizmalar üzerinden nörolojik hastalıklar, üreme sistemi bozuklukları ve kanser gibi ciddi sağlık sorunlarına zemin hazırlayabildiği görülmektedir. Strobilurin ve azol grubu fungisitlerin bu bağlamda özellikle dikkat çektiği, mevcut güvenlik eşiklerinin kronik maruziyet senaryoları için yeterince koruyucu olmayabileceği anlaşılmaktadır. Tüm bu bulgular, fungisit kullanımına ilişkin yaklaşımların yalnızca verim odaklı bir bakış açısından çıkıp insan sağlığını, çevresel sürdürülebilirliği ve gıda güvenliğini eşit ağırlıkla göz önünde bulunduran bütüncül bir perspektife taşınması gerektiğini vurgulamaktadır. Bu noktada JMPR, EFSA ve EPA gibi uluslararası kuruluşların geliştirdiği bilimsel değerlendirme sistemleri önemli bir çerçeve sunmakla birlikte, farklı kimyasalların birlikte yarattığı etkiler ve hassas gruplara yönelik riskler gibi konularda bu sistemlerin güncellenmesi ve güçlendirilmesi gerekmektedir.

5.2. Öneriler

Fungisit kullanımından kaynaklanan toksikolojik ve çevresel risklerin azaltılması, çok boyutlu ve birbirini tamamlayan stratejilerin bir arada hayata geçirilmesini gerektirmektedir. Bu kapsamda öncelikli adım, fungisit uygulamalarını bilimsel verilere dayalı olarak planlamak ve her uygulamada doz, zamanlama ve sıklık açısından gereklilik ilkesini gözetmektir. Gereksiz ve aşırı kullanımdan kaçınmak, hem çevresel kirliliği hem de insan sağlığına yönelik riskleri doğrudan azaltacaktır. Kimyasal mücadelenin tek başına bir çözüm olarak benimsenmesi yerine, biyolojik, kültürel ve mekanik yöntemlerle bütünleştirildiği entegre mücadele yaklaşımlarının yaygınlaştırılması bu açıdan kritik öneme sahiptir. Bu yaklaşım, fungisit kullanımını en aza indirirken bitki koruma etkinliğini de korumaktadır. Yeni nesil fungisit geliştirme süreçlerinde ise hedefe özgü, çevre dostu ve düşük toksisiteli aktif maddelere öncelik verilmesi, biyolojik kökenli fungisitlerin teşvik edilmesi ve nanoteknoloji tabanlı kontrollü salım sistemleri gibi ileri teknolojilerin araştırmalara dahil edilmesi gerekmektedir. Gıda ürünleri ve çevresel ortamlarda fungisit kalıntılarının düzenli olarak izlenmesi, ulusal ve uluslararası sınır değerlerle uyumun denetlenmesi ve analiz altyapısının güçlendirilmesi de vazgeçilmez bir gereklilik olarak öne çıkmaktadır. Çiftçiler, uygulayıcılar ve tüm paydaşların fungisitlerin riskleri, doğru kullanımı ve alternatif mücadele yöntemleri konusunda bilinçlendirilmesi, toksikolojik risklerin kaynakta azaltılmasında belirleyici bir etkendir. Fungisit kalıntılarının çevreden uzaklaştırılmasında ise mikroorganizma temelli parçalanma süreçleri, bitkilerle gerçekleştirilen temizleme uygulamaları ve ileri oksidasyon yöntemleri gibi çevre dostu teknolojilerin geliştirilmesi ve yaygınlaştırılması desteklenmelidir. Son olarak, fungisitlerin farklı kimyasallarla birlikte kullandığında ortaya çıkan etkiler, uzun süreli düşük doz maruziyetin kronik sonuçları ve hassas gruplardaki özel riskler gibi alanlarda kapsamlı ve çok disiplinli araştırmalara olan ihtiyaç giderek artmaktadır. Toksikoloji, ekoloji ve moleküler biyoloji gibi farklı bilim dallarının iş birliğiyle yürütülecek bu çalışmalar, hem bilimsel bilgi birikimini derinleştirecek hem de risk yönetimi süreçlerine daha güvenilir bir temel oluşturacaktır.

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NANO-BİYOTEKNOLOJİK YAKLAŞIMLARLA BİTKİYLE ARINDIRMANIN GELİŞTİRİLMESİ: MOLEKÜLER MEKANİZMALAR, OMİKS TEKNOLOJİLERİ VE ENTEGRE STRATEJİLER

ENHANCING PHYTOREMEDIATION THROUGH NANO-BIOTECHNOLOGICAL APPROACHES: MOLECULAR MECHANISMS, OMICS TECHNOLOGIES, AND INTEGRATED STRATEGIES

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ÖZET

Bu çalışma, küresel bir çevre sorunu haline gelen ağır metal kirliliğiyle mücadelede kullanılan fitoremediasyon (bitkiyle arındırma) yöntemini; nanoteknoloji, genetik mühendisliği ve omiks teknolojileri ekseninde kapsamlı bir şekilde ele almaktadır. Geleneksel fitoremediasyon süreçleri, bitkilerin sınırlı büyüme hızı ve düşük metal birikim kapasitesi gibi nedenlerle sahada istenen verimi her zaman sağlayamamaktadır. Ancak son yıllarda geliştirilen nano-fitoremediasyon yaklaşımları, nanopartiküllerin bitki stres toleransını artırma ve metal iyonlarını mobilize etme yetenekleri sayesinde bu engelleri aşmaktadır. Özellikle CRISPR/Cas9 tabanlı gen düzenleme teknikleri ve multi-omiks verilerinin yapay zeka ile entegrasyonu, bitkilerin detoksifikasyon mekanizmalarını hücresel düzeyde optimize ederek daha dirençli ve etkin türlerin geliştirilmesine olanak tanımaktadır. Derlemede ayrıca; biyokömür (biochar), nanoparçacıklar ve faydalı mikroorganizmaların bir arada kullanıldığı hibrit sistemlerin, kirletici gideriminde %90'lara varan yüksek başarı oranları sunduğu vurgulanmaktadır. Sonuç olarak bu çalışma; sürdürülebilir bir çevre yönetimi için bitki, toprak ve teknoloji arasındaki dinamik etkileşimi bütüncül bir yaklaşımla değerlendirmekte ve gelecek araştırmalar için döngüsel ekonomi odaklı bir yol haritası sunmaktadır.

Anahtar Kelimeler: Fitoremediasyon, Nanoteknoloji, CRISPR/Cas9, Omiks Teknolojileri, Ağır Metaller, Biyokömür.

ABSTRACT

This study provides a comprehensive evaluation of phytoremediation a sustainable strategy for mitigating heavy metal pollution by integrating nanotechnology, genetic engineering, and omics technologies. Conventional phytoremediation often faces limitations such as slow plant growth, low biomass production, and limited metal uptake under high toxicity. However, recent advances in nano-phytoremediation offer promising solutions; nanoparticles enhance plant stress tolerance and improve the bioavailability of metals, thereby overcoming these physiological constraints. The integration of CRISPR/Cas9 based genome editing and multi-omics data, coupled with artificial intelligence, allows for the precise optimization of detoxification pathways at the molecular level, leading to the development of highly resilient plant varieties. Furthermore, the review highlights that hybrid systems involving the synergistic use of biochar, nanoparticles, and beneficial microorganisms can achieve contaminant removal efficiencies as high as 90-97%. In addition to technological advancements, this paper critically analyzes the ecotoxicological risks associated with nanoparticles, including their long-term impact on soil microbiota and potential entry into the food chain. Ultimately, this review establishes a new paradigm in environmental biotechnology by emphasizing a holistic approach that balances remediation efficiency with ecological safety, aligned with the principles of a circular economy.

Keywords: Phytoremediation, Nanotechnology, CRISPR/Cas9, Omics Technologies, Heavy Metals, Biochar.

GİRİŞ

Sanayileşmenin hızlanması, yoğun tarımsal uygulamalar ve plansız kentleşme, toprak ve su ekosistemlerinde ağır metal kirliliğini küresel bir endişe hâline getirmiştir (Yerli ve ark., 2020). Ağır metaller biyolojik olarak parçalanamayan, çevrede uzun süre kalan ve bitki gelişimi ile insan sağlığı üzerinde toksik etkiler oluşturan kirleticilerdir (Taylan ve Özkoç, 2007; Yerli ve ark., 2020). Fiziksel ve kimyasal arıtma teknikleri yüksek maliyetli olduğundan ve ikincil kirlilik riski taşıdığından, çevre dostu alternatifler araştırılmaktadır. Bu bağlamda bitkilerle kirleticilerin uzaklaştırılmasını temel alan fitoremediasyon, sürdürülebilir bir seçenek olarak belirgin şekilde gündeme gelmiştir (Salt ve ark., 1998). Fitoremediasyon; kirleticilerin bitkilerin kök, gövde ve yaprak organları aracılığıyla alınması, stabilize edilmesi veya zararsız hale getirilmesini kapsar (Pilon Smits, 2005). Ancak bu yöntemin yaygın uygulanabilirliğini sınırlayan temel faktörler arasında düşük biyokütle üretimi, sınırlı metal alım kapasitesi ve yüksek toksisite koşullarında büyüme baskısı yer alır (Chaney ve ark., 1997; Nagajyoti ve ark., 2010). Nanoteknoloji ve genetik biyoteknoloji, bu kısıtlamaları aşmada potansiyel çözümler sunan iki ana bilimsel yaklaşım olarak öne çıkmaktadır. Nanoteknoloji, nanopartiküller (NP)'in yüksek yüzey alanı ve reaktivitesi sayesinde bitki stres toleransını artırması, metal biyoyararlanımını iyileştirmesi ve fitoremediasyon verimliliğini yükseltmesi açısından umut vaat etmektedir (Prakash ve Smitha-Chandran, 2023; Sharma ve ark., 2025). Diğer yandan, modern genetik teknikler, özellikle düzenli aralıklarla kümelenmiş kısa palindromik tekrarlar ''Clustered Regularly Interspaced Short Palindromic Repeats'' (CRISPR/Cas9) tabanlı gen düzenleme, metal taşıyıcı proteinleri, şelatör üretimi ve stres yanıtını düzenleyen genlerin hedefli modifikasyonuyla bitkilerde fitoremediasyon kapasitesini doğrudan artırmayı amaçlamaktadır (Nayeri ve ark., 2023; Garg ve ark., 2025). Her iki yaklaşımın ayrı ayrı etkileri iyi bir şekilde çalışılmışken, nanoteknoloji ve genetik mühendisliğinin birlikte kullanıldığı entegre stratejiler hâlâ görece yeni bir araştırma alanıdır ve bu derlemede bu entegrasyonun potansiyeli detaylı olarak ele alınmaktadır. Bu alan hızla gelişmekte olup, mevcut çalışmalar genellikle tekil yaklaşımlara odaklanmaktadır. Entegre nano-genetik-omiks yaklaşımları sınırlı sayıda ele alınmıştır.

FİTOREMEDİASYON MEKANİZMALARI

Fitoremediasyon, kirleticilerin bitkiler tarafından alınmasını ve/veya çevresel olarak immobilize edilmesini sağlayan biyolojik bir süreçtir. Fitoekstraksiyon, ağır metalleri bitki kökleri aracılığıyla absorbe ederek toprak üstü organlarda biriktirmeyi ve sonrasında kirletici yükün fiziksel olarak toparlanmasını ifade eder (Ghosh ve Sing, 2005; Sharma ve ark., 2024).

Özellikle hiperakümülatör bitki türlerinde bu birikim topraktaki metal konsantrasyonunun önemli ölçüde düşmesine yol açabilir. Fitostabilizasyon, kirleticilerin kök çevresinde immobilize edilmesini sağlayarak çevresel yayılımı azaltır; rizofiltrasyon ise su ortamlarında kök aracılığıyla metal adsorpsiyonu sağlar (Berti ve Cunningham, 2000; Kalkan ve ark., 2011).

Daha az yaygın olmakla birlikte fitodegradasyon ve fitovolatilizasyon gibi mekanizmalar organik kirleticilerin parçalanması veya uçucu formda uzaklaştırılması gibi süreçleri kapsar (Kumari ve ark., 2020; Sharma ve ark., 2025). Buna rağmen geleneksel fitoremediasyonun etkinliği; çevresel koşullar, bitki türü, metal türü ve fizyolojik stres gibi çok sayıda faktöre bağlı olarak sınırlı kalabilmektedir.

NANOTEKNOLOJİ DESTEKLİ FİTOREMEDİASYON

Nanoteknoloji, bitkilerin fitoremediasyon verimliliğini artırmada son yıllarda öncelikli bir araştırma alanı hâline gelmiştir (Gulzar ve Mazumder, 2022; Gomes, 2025). Nanopartiküller, çevre kirliliğinin giderilmesinde bitkilerin biyolojik sınırlarının ötesine geçmesine yardımcı olan çok fonksiyonlu araçlar olarak tanımlanmaktadır (Guerra ve ark., 2018). Nanoteknoloji ve fitoremediasyonun entegrasyonu "nano-fitoremediasyon" olarak literatürde yer almakta ve bu alandaki çalışmalar, NP'ler metal iyonlarının biyoyararlanımını artırdığı**,** bitki stres toleransını yükselttiği ve genel olarak kirleticilerin ortamdan uzaklaştırılmasını hızlandırdığına dair güçlü kanıtlar sunmaktadır (Prakash ve Smitha-Chandran, 2023). Örneğin, kapsamlı bir derlemede NP'ler çevresel temizlemede fitoremediasyon kapasitesini önemli ölçüde artırdığı, kirletici biyoyararlanımını iyileştirdiği ve bitki köklerinin metabolik aktivitelerini modüle ettiği bildirilmiştir (Sharma ve ark., 2025). Ayrıca NP'ler ***in situ***

uygulamalarda metal iyonlarının toprak bağlanma formunu değiştirerek bitki tarafından alınabilirliği artırdığı raporlanmıştır; bu, özellikle ağır metal kirleticilerinin bitki köklerine daha kolay ulaşmasını sağlamaktadır (Tunca, 2015; Song ve ark., 2019). Nanopartiküller bu süreçte çok yönlü etki göstermektedir: sadece kirletici alımını artırmakla kalmayıp, aynı zamanda kök ve rizosfer mikro çevresindeki kimyasal ortamı değiştirerek enzim aktivitelerini ve antioksidan savunma mekanizmalarını desteklemektedir. Nano-fitoremediasyon yaklaşımlarının ağır metal çözünürlüğünü ve bitki performansını artırdığı, bazı durumlarda metal uzaklaştırma oranını %80-97 gibi yüksek değerlere çıkardığı bildirilmektedir (Sharma ve ark., 2025). Bu yüksek oranlar, NP'lerin fitoremediasyonu sadece bir tamamlayıcı strateji değil, aynı zamanda etkin temizleme için gerekli bir araç haline getirebileceğini göstermektedir. Bununla birlikte nanoteknoloji uygulamalarının çevresel etkileri de dikkatle değerlendirilmelidir. Özellikle nano-gümüş gibi bazı NP'ler için ekotoksik etki riskleri üzerine yapılan çalışmalar, NP'ler çevresel sistemler üzerinde olumsuz yan etkilere sahip olabileceğini vurgulamaktadır (Bondarenko ve ark., 2013). Bu durum, nano-fitoremediasyonun hem etkinliğinin hem de çevresel güvenliğinin optimize edilmesini zorunlu kılmaktadır.

GENETİK VE MOLEKÜLER YAKLAŞIMLAR

Genetik mühendislik, bitkilerin ağır metal toleransı ve birikim kapasitesini artırmak amacıyla kullanılan önemli bir yaklaşımdır. Bu kapsamda metal taşıyıcı proteinler, metallotiyoneinler, fitokelatinler ve antioksidan enzim sistemleri ile ilişkili genlerin düzenlenmesi ön plana çıkmaktadır (Shourie ve ark., 2024). CRISPR/Cas9 gibi genom düzenleme teknikleri, hedef genlerin hassas bir şekilde modifiye edilmesine olanak sağlayarak bitkilerin metal stresine karşı adaptasyonunu artırmaktadır (Garg ve ark., 2025). Bu yaklaşımlar, bitkilerin sadece metal alım kapasitesini değil aynı zamanda stres toleransını ve metabolik uyumunu da geliştirmektedir. Ancak genetik modifikasyon süreçlerinin kompleks yapısı ve çoklu gen etkileşimleri, bu uygulamaların dikkatli planlanmasını gerektirmektedir.

ENTEGRE NANOTEKNOLOJİ VE GENETİK YAKLAŞIMLAR

Nanoteknoloji ve genetik mühendisliğinin birlikte kullanımı, fitoremediasyonun etkinliğini artırmada yeni nesil bir yaklaşım olarak değerlendirilmektedir. Nanopartiküller, genetik materyallerin bitki hücrelerine taşınmasında taşıyıcı sistemler olarak kullanılabilmekte ve gen düzenleme verimliliğini artırabilmektedir (Yan ve ark., 2022; Al-Amri, 2026). Bu entegrasyon sayesinde hem kirletici biyoyararlanımı artırılmakta hem de bitkilerin genetik düzeyde stres yanıtı optimize edilmektedir. Sonuç olarak, metal toleransı artmakta, oksidatif stres azalmakta ve fitoremediasyon süreci hızlanmaktadır. Ancak bu yaklaşımların çevresel etkileri ve uzun vadeli sonuçları hâlen araştırılmaktadır.

OMİKS VE GENOM DÜZENLEME TEKNOLOJİLERİ

Omiks teknolojileri, fitoremediasyon süreçlerinin moleküler düzeyde anlaşılmasına önemli katkılar sağlamaktadır. Genomik, transkriptomik, proteomik ve metabolomik yaklaşımlar sayesinde bitkilerin ağır metal stresine karşı verdiği yanıtlar çok boyutlu olarak analiz edilebilmekte; gen ekspresyonu, protein sentezi ve metabolik yolaklardaki değişimler ayrıntılı şekilde ortaya konulmaktadır (Gul ve ark., 2025; Khan ve ark., 2025a). Özellikle transkriptomik analizler (RNA-seq), ağır metal stresine maruz kalan bitkilerde metal taşıyıcı proteinler, antioksidan enzimler ve sülfür metabolizması ile ilişkili genlerin farklılaşmış ekspresyonunu ortaya koymaktadır. Bunun yanı sıra, metabolomik çalışmalar, fitokelatinler, organik asitler ve antioksidan bileşikler gibi detoksifikasyon sürecinde rol oynayan metabolitlerin dinamik değişimini belirleyerek ağır metal tolerans mekanizmalarının anlaşılmasına katkı sağladığı bildirilmiştir (Singh ve ark., 2016). Ayrıca multi-omiks yaklaşımlar, bitki ve mikroorganizma etkileşimlerini de kapsayacak şekilde genişletilmiş olup, rizosferde gerçekleşen biyokimyasal süreçlerin ve mikrobiyal katkıların sistem düzeyinde analiz edilmesine olanak tanımaktadır. Bu bütüncül yaklaşım, yalnızca bitki içi mekanizmaların değil, aynı zamanda fitoremediasyon sisteminin tamamının optimize edilmesine katkı sağlamaktadır (Khan ve ark., 2025b). Bu veriler doğrultusunda, ağır metal toleransı ve akümülasyonu ile ilişkili aday genler belirlenmekte ve bu genler CRISPR/Cas9 gibi genom düzenleme

teknolojileri ile hedeflenerek bitkilerin fitoremediasyon kapasitesi artırılmaktadır. CRISPR tabanlı çalışmalar, özellikle metal taşıyıcı genler, metallotiyoneinler ve fitokelatin sentez yolakları üzerinde yoğunlaşmakta ve bu genlerin modifikasyonu ile bitkilerde hem metal alımı hem de toleransın önemli ölçüde artırılabildiği gösterilmektedir (Garg ve ark., 2025). Son yıllarda, omiks verilerinin yapay zeka ile entegrasyonu, fitoremediasyon araştırmalarında yeni bir paradigma oluşturmuştur. Büyük veri setlerinin analizi sayesinde kritik gen ağları, metabolik yollar ve bitki-mikroorganizma etkileşimleri modellenebilmekte; bu sayede hedef bitki türlerinin seçimi ve genetik iyileştirme stratejileri daha hassas şekilde belirlenebilmektedir (Gul ve ark., 2025).

TOPRAK–BİTKİ–NANOPARÇACIK ETKİLEŞİMLERİ

Nanopartiküller, toprak-bitki sisteminde kirleticilerin mobilitesini, biyoyararlanımını ve taşınımını değiştirerek fitoremediasyon sürecini doğrudan etkileyen önemli bileşenlerdir (Badamasi ve ark., 2026). Nanopartiküller, yüksek yüzey alanı ve reaktif özellikleri sayesinde ağır metallerle kompleks oluşturabilmekte, bu sayede kirleticilerin çözünürlüğünü artırarak bitki kökleri tarafından alımını kolaylaştırmaktadır (Gomes, 2025). Toprak ortamında NP'lerin davranışı; pH, organik madde içeriği, katyon değişim kapasitesi ve redoks potansiyeli gibi faktörlere bağlı olarak değişmektedir (Suazo-Hernández ve ark.,2023). Örneğin düşük pH koşullarında metal iyonlarının çözünürlüğü artarken, NP'ler bu süreçte yüzey kompleksleşmesi ve iyon değişimi mekanizmaları aracılığıyla metal mobilitesini daha da artırabilmektedir. Buna karşılık, yüksek organik madde içeriği NP'lerin yüzeyine bağlanarak agregasyon oluşturabilir ve bu durum onların biyoyararlanım üzerindeki etkisini sınırlayabilir (Wen ve ark., 2018). Bitki düzeyinde ise NP'ler, kök yüzeyinde adsorbe olarak veya apoplastik ve simplastik yollarla bitki dokularına taşınabilmektedir. Özellikle küçük boyutlu NP'ler, hücre duvarı porlarından geçerek ksilem ve floem aracılığıyla bitkinin üst kısımlarına taşınabilmektedir (Gomes, 2025). Bu durum, kirleticilerin bitki içerisinde daha etkin bir şekilde taşınmasını ve biriktirilmesini sağlamaktadır. Ayrıca bazı NP'lerinin kök/sürgün uzunluğu ve biyokütle artışı sağladığı ve böylece metal alım kapasitesini yükselttiği bildirilmektedir (Can ve Gürel, 2023; Zaman ve ark., 2024). Nanopartiküller aynı zamanda bitkilerde fizyolojik ve biyokimyasal süreçleri de etkilemektedir. Antioksidan enzim aktivitelerini (SOD, CAT, POD) artırarak reaktif oksijen türlerinin (ROS) neden olduğu oksidatif stresi azaltmakta ve bitkinin ağır metal stresine karşı toleransını artırmaktadır (Mansoor ve ark., 2023). Bunun yanı sıra, fotosentetik pigment içeriğini ve su kullanım etkinliğini iyileştirerek bitki büyümesini ve biyokütle üretimini teşvik etmektedir (Gomes, 2025). Rizosfer düzeyinde, NP'ler bitki-mikroorganizma etkileşimlerini de önemli ölçüde etkilemektedir. Bazı NP'ler, faydalı mikroorganizmaların aktivitesini artırarak kirleticilerin biyolojik dönüşümünü hızlandırırken, bazı durumlarda mikrobiyal çeşitliliği baskılayarak olumsuz etkiler oluşturabilmektedir. Bu nedenle NP'nin türü, konsantrasyonu ve uygulama şekli kritik öneme sahiptir (Khan ve ark., 2025b).

FARKLI KİRLETİCİ TÜRLERİNE GÖRE FİTOREMEDİASYON

Geleneksel olarak fitoremediasyon, ağır metallerin uzaklaştırılmasına odaklanmış olsa da günümüzde bu yöntem çok daha geniş bir kirletici yelpazesini kapsamaktadır. Bunlar arasında pestisitler, mikroplastikler ve çeşitli organik kirleticiler yer almaktadır (Rajput ve ark., 2024; Dhanapal ve ark., 2024). Bu kirleticiler, toprak ve su ekosistemlerinde birikerek hem bitki hem de insan sağlığı için ciddi riskler oluşturabilmektedir.

Bitkiler, bazı pestisitleri ve farmasötik atıkları metabolik yollar aracılığıyla absorbe edebilmekte ve kısmen detoksifiye edebilmektedir (Gupta ve ark., 2026). Nano-destekli uygulamalarda, metal oksit NP'ler ve karbon bazlı NP'ler kirleticilerin çözünürlüğünü ve bitki tarafından alınabilirliğini artırarak fitoremediasyon etkinliğini yükseltmektedir (Ali ve ark., 2026; Dixit ve ark., 2026).

Mikroplastikler, toprakta kirleticileri taşıyabilen ve bitkiler tarafından alınabilen fiziksel taşıyıcılar olarak işlev görebilmektedir. Nano-destekli sistemlerde, NP'ler mikroplastiklerin yüzeyine bağlanarak organik kirleticilerin mobilitesini artırabilir ve bitki kökleri aracılığıyla uzaklaştırılmasını kolaylaştırabildiği bildirilmiştir (Koul ve ark., 2025; Jassal ve ark., 2025).

Nano-destekli fitoremediasyon, kirleticilerin biyoyararlanımını artırmasının yanı sıra bitkilerin stres toleransını da yükseltmektedir. Örneğin, titanyum dioksit (TiO_2), çinko oksit (ZnO) ve karbon

nanotüpler gibi NP'ler; fotosentetik verim, antioksidan sistem aktivitesi ve biyokütle üretimini destekleyerek kirletici alımını optimize etmektedir (Sharma ve ark., 2025). Bu sayede yeni nesil kirleticilerin giderilmesi daha etkin ve hızlı hale gelmektedir.

HİBRİT YAKLAŞIMLAR

Hibrit fitoremediasyon sistemleri, biochar, nanoparçacıklar ve faydalı mikroorganizmaların birlikte kullanılması ile fitoremediasyon etkinliğini önemli ölçüde artırmaktadır. Biochar, yüksek yüzey alanı ve gözenekli yapısı sayesinde topraktaki ağır metallerin ve diğer kirleticilerin immobilizasyonunu sağlar, böylece kirleticilerin bitki dokularına aşırı geçişini sınırlar. Aynı zamanda toprak su tutma kapasitesini ve havalanmasını iyileştirerek kök gelişimini desteklediği birçok araştırmacı tarafından bildirilmiştir (Ghosh ve Maiti, 2021; Anne ve ark., 2024; Fang ve ark., 2025). Nanopartiküller, özellikle metal oksitler ve karbon bazlı NP'ler, kirleticilerin çözünürlüğünü ve bitki tarafından alınabilirliğini artırmaktadır. Bu NP'ler, bitki köklerinde antioksidan sistemlerini uyararak oksidatif stresin azalmasına ve bitki büyümesinin desteklenmesine katkı sağlar (Zhou ve ark., 2020; Ayanda ve ark., 2024). Hibrit sistemlerde, biochar üzerinde immobilize edilen mikroorganizmalar, nanoparçacıklarla birlikte kullanıldığında sinerjik etkiler göstermektedir. Bu etkileşim sayesinde hem metal ve organik kirleticilerin alımı optimize edilmekte hem de bitkilerde biyokütle üretimi artmaktadır. Örneğin, biochar ve nanoparçacık kombinasyonu, kök rizosferinde mikroorganizmaların aktivitesini artırarak kirleticilerin biyolojik dönüşümünü hızlandırmakta ve fitoremediasyon sürecini daha verimli hâle getirmektedir (Yasin ve ark., 2024; Fan ve ark., 2024; Mustafa ve ark., 2026). Son yıllarda yapılan araştırmalar, hibrit sistemlerin yalnızca metal temizleme ile sınırlı kalmayıp organik kirleticiler ve mikroplastiklerin uzaklaştırılmasında da etkin olduğunu göstermektedir. Bu sistemler, sürdürülebilir çevre yönetimi ve toprak rehabilitasyonu açısından önemli bir potansiyel sunmaktadır (Dhanapal ve ark., 2024; Khan ve ark., 2025b).

ÇEVRESEL RİSKLER VE EKOTOKSİKOLOJİK DEĞERLENDİRME

Nanofitoremediasyonun etkinliğine rağmen, nanopartikül ekotoksikliği, uzun vadeli çevresel kalıcılık ve düzenleyici boşluklar gibi zorluklar dikkatli bir değerlendirme gerektirmektedir (Badamasi ve ark., 2026). Yüksek konsantrasyonlarda, toksik ajanlar olarak ROS, oksidatif strese neden olabilir, bitki fotosentezini, solunumunu etkileyebilir ve hatta bitki hücre ölümüne yol açarak bitki büyümesini ve ağır metal birikimini etkileyebilir (Berrios ve Rentsch, 2022).

Buna ek olarak, NP'lerin toprak mikroorganizma toplulukları üzerindeki etkileri de önemli bir risk faktörüdür (Xu ve ark., 2022). Ayrıca, bazı metal NP'ler, faydalı mikrobiyal aktiviteleri inhibe ederek toprak sağlığını ve biyolojik döngüleri bozabilmektedir (Dinesh ve ark., 2012). Fitovolatilizasyon, aslında ağır metalleri yok etmek yerine sadece yerlerini değiştirdiği için beraberinde ciddi riskler getiren bir yöntemdir. Temel sorun, bitkinin topraktan çektiği metalleri gaz formuna dönüştürüp atmosfere salmasıdır; bu uçucu bileşikler hava akımlarıyla çok uzak mesafelere taşınarak kirliliği kontrolsüz bir şekilde geniş bir alana yayabilir. Havaya salınan bu maddeler tekrar yeryüzüne çökerek su ekosistemlerine karıştığında, besin zinciri aracılığıyla insanlara kadar ulaşabilen ve çok daha zehirli olan formlara dönüşerek çevresel tehlikeyi daha da büyütebilir (Gupta ve Yadav, 2024). Ekotoksik etkilerin şiddeti, NP'nin türüne, boyutuna, konsantrasyonuna ve çevresel koşullara bağlı olarak değişmektedir (Bour ve ark., 2015). Bu nedenle nano fitoremediasyon uygulamalarında hem etkinliği hem de çevresel güvenliği optimize etmek için kapsamlı risk değerlendirmeleri yapılması önerilmektedir. Bu kapsamda, NP'lerin biyolojik dağılımı, çözünürlüğü, toksik eşik değerleri ve uzun vadeli etkileri sistematik olarak incelenmelidir (Yasin ve ark., 2024; Kumar ve ark., 2026).

SONUÇ VE GELECEK PERSPEKTİFLER

Modern çevre teknolojilerinde nanoteknoloji ve genetik mühendisliğinin stratejik birleşimi, kirletici temizleme (fitoremediasyon) süreçlerinde yeni bir dönemi temsil etmektedir. Bu sinerji, yalnızca bitkilerin metal tutma kapasitesini artırmakla kalmayıp, CRISPR/Cas9 gibi ileri genom düzenleme araçlarıyla bitki metabolizmasını stres faktörlerine karşı daha dirençli hale getirmektedir. Nano-taşıyıcı

sistemlerin genetik modifikasyonlarla entegre edilmesi, bitkinin hem fiziksel büyümesini (biyokütle artışı) hem de hücresel düzeydeki savunma mekanizmalarını (antioksidan sistemler) aynı anda optimize etmektedir.

Geleceğe yönelik stratejilerde, bu teknolojik gelişmelere yapay zeka ve multi-omiks analizlerinin dahil edilmesi, hangi bitki türünün hangi kirletici için en uygun olduğunun önceden kestirilmesini sağlayacaktır. Ancak bu teknolojik sıçramanın bir "güvenlik" boyutu da bulunmaktadır. Nanopartiküllerin toprak ekosistemi ve besin zinciri üzerindeki uzun vadeli etkileri, henüz tam olarak aydınlatılamamış kritik bir araştırma alanıdır. Bu nedenle, uygulamaların sadece verimlilik odaklı değil, aynı zamanda ekotoksikolojik riskleri minimize eden bütüncül bir yaklaşımla tasarlanması şarttır.

Son olarak, fitoremediasyon süreci sadece temizlik ile bitmemelidir. Hasat edilen kontamine biyokütlenin biochar gibi katma değerli ürünlere dönüştürülmesi, döngüsel ekonomi prensipleriyle uyumlu, sürdürülebilir bir çevre yönetimi modeli sunmaktadır. Sonuç olarak; toprak, bitki ve nanopartikül arasındaki bu dinamik etkileşimi tüm boyutlarıyla kavramak, geleceğin ekolojik rehabilitasyon stratejilerinin temel taşı olacaktır.

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SEPSİS PATOFİZYOLOJİSİNDE ENDOKANNABİNOİD SİSTEMİN ROLÜ: CB1 VE CB2 RESEPTÖR MODÜLASYONUNUN TERAPÖTİK POTANSİYELİ

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ÖZET

Sepsis, vücudun enfeksiyona karşı verdiği kontrolsüz ve aşırı inflamatuar (yangısal) yanıt sonucu ortaya çıkan, organ yetmezliğiyle seyreden ve hayati tehlike arz eden bir tablodur. Endokannabinoid sistem (EKS), özellikle de kannabinoid tip 1 (CB1) ve de kannabinoid tip 2 (CB2) reseptörleri, sepsisin patofizyolojisinde çift taraflı bir kılıç gibi kritik roller üstlenir. Sepsis ve kannabinoid reseptörleri arasındaki ilişki üzerine yapılan çalışmalar, temel olarak CB1 blokajı ve CB2 aktivasyonu stratejilerine odaklanmış durumdadır. Genellikle farelerde Çekal Ligasyon ve Delme (ÇLD) yöntemiyle yapıan sepsis modellemelerinde endokannabinoidlerin (anandamid) aşırı salgılandığı ve damarlardaki CB1 reseptörlerine bağlanarak kan basıncını tehlikeli düzeyde düşürdüğü görülmüştür. CB1 reseptör antagonizmasının ortalama arteriyel basınçta yaklaşık %30-40 oranında bir iyileşme sağlayarak vasküler çöküşü stabilize ettiği görülmektedir. Bağışıklık sistemi hücreleri (makrofajlar, nötrofiller) üzerindeki CB2 reseptörlerini hedef alan çalışmalar daha umut verici sonuçlar sunmaktadır. Nitekim CB2 agonistleri ile yapılan uygulamalar, TNF-alfa ve IL-6 gibi pro-inflamatuar belirteçlerin seviyelerini %50'nin üzerinde baskılayabilmektedir. Sepsise bağlı çoklu organ yetmezliği üzerine odaklanan araştırmalar, kannabinoid sisteminin antioksidan kapasiteyi artırdığını bildirmektedir. Beyindeki mikrogliya hücrelerinin CB2 üzerinden baskılanmasının, sepsis sonrası oluşabilecek beyin hasarını ve bilişsel disfonksiyonu azalttığı bulunmuştur. Sonuç olarak, CB1 reseptörlerinin antagonizması septik şoktaki vasküler yetmezliği iyileştirirken; CB2 reseptörlerinin aktivasyonunun sistemik inflamasyonu ve organ hasarını sınırlayarak sağkalımı artırmaktadır. Bu ikili yaklaşım, sepsisin patofizyolojik karmaşıklığına karşı yeni ve güçlü bir terapötik pencere sunmaktadır.

Anahtar Kelimeler: Sepsis, Çekal Ligasyon, Endokannabinoid, CB1, CB2

THE ROLE OF THE ENDOCANNABINOID SYSTEM IN THE PATHOPHYSIOLOGY OF SEPSIS: THERAPEUTIC POTENTIAL OF CB1 AND CB2 RECEPTOR MODULATION

ABSTRACT

Sepsis is a life-threatening condition resulting from an uncontrolled and excessive inflammatory response of the body to infection, leading to organ failure. The endocannabinoid system (ECS), particularly cannabinoid type 1 (CB1) and cannabinoid type 2 (CB2) receptors, plays critical roles in the pathophysiology of sepsis, acting like a double-edged sword. Studies on the relationship between sepsis and cannabinoid receptors have primarily focused on CB1 blockade and CB2 activation strategies. Sepsis modeling, often performed in mice using the Cecal Ligation and Puncture (CLD) method, has shown that excessive secretion of endocannabinoids (anandamide) leads to dangerously low blood pressure by binding to CB1 receptors in the vessels. CB1 receptor antagonism appears to stabilize vascular collapse by providing approximately a 30-40% improvement in mean arterial pressure. Studies targeting CB2 receptors on immune system cells (macrophages, neutrophils) are yielding more promising results. Indeed, applications with CB2 agonists can suppress levels of pro-inflammatory markers such as TNF-alpha and IL-6 by over 50%. Research focusing on sepsis-related multiple organ failure reports that the cannabinoid system enhances antioxidant capacity. Suppression of microglia cells in the brain via CB2 has been found to reduce brain damage and cognitive dysfunction that may occur after sepsis. In conclusion, antagonism of CB1 receptors improves vascular insufficiency in septic shock, while activation of CB2 receptors increases survival by limiting systemic inflammation and organ damage. This dual approach offers a new and powerful therapeutic window against the pathophysiological complexity of sepsis.

Keywords: Sepsis, Cecal Ligation, Endocannabinoid, CB1, CB2

INTRODUCTION

Sepsis is a life-threatening organ dysfunction resulting from a disruption in the regulation of the host's immune response to infection. Despite advances in modern medicine, sepsis remains a major health problem in intensive care units due to its high mortality rates and complex pathophysiology. It is also a costly condition that places a significant economic burden on healthcare systems (Giustozzi et al., 2021). Individuals who survive a sepsis attack often face problems including chronic kidney disease, various cardiovascular and cognitive dysfunctions. The World Health Organization has officially identified sepsis as a major public health problem and a leading cause of death in children worldwide (Shih et al., 2017).

Recent research has shown that the endocannabinoid system (ECS), known as the body's homeostatic regulator, plays a central role in the development and progression of sepsis. The ECS consists of endocannabinoid ligands, synthesis/degradation enzymes, and G-protein coupled receptors, specifically cannabinoid type 1 (CB1) and cannabinoid type 2 (CB2). Endocannabinoid ligands are molecules naturally produced by our bodies, similar to compounds found in the cannabis plant. During sepsis, anandamide (AEA) and 2-AG levels, in particular, increase significantly. AEA is the main actor in sepsis, lowering blood pressure by relaxing blood vessels. 2-AG is more effective in managing immune cells. FAAH and MAGL enzymes are the cleanup crew that breaks down these molecules after the signaling stops (Lafreniere and Lehmann, 2017). CB1 receptors are predominantly found in the brain and the inner lining of blood vessels (endothelium). CB2 receptors are predominantly found in immune system cells (macrophages, spleen, T-cells) (Figure 1). They have the potential to reduce inflammation in sepsis. Overactivation of this system in sepsis, while deepening vascular collapse, also presents a potential target for immune modulation.

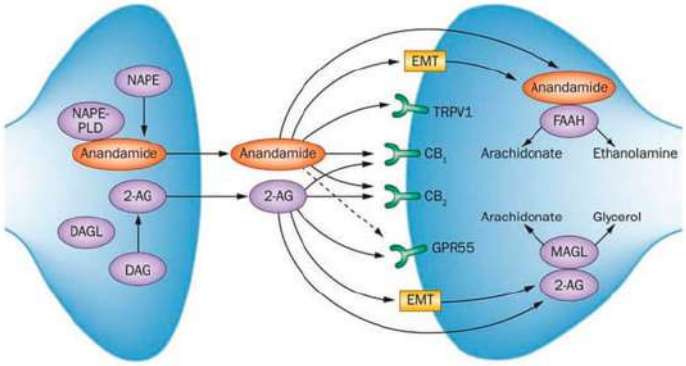


Figure 1. Summary of the endocannabinoid system: highlighting key endocannabinoids, cannabinoid receptors, and synthesis/degradation enzymes (Lafreniere and Lehmann, 2017).

In the pathophysiological process of sepsis, endocannabinoids, particularly anandamide, are known to deepen septic shock by raising blood pressure to dangerous levels via vascular CB1 receptors. On the other hand, activation of CB2 receptors in immune system cells such as macrophages and neutrophils stands out as a more promising therapeutic target for curbing systemic inflammation (Thai et al., 2025). In light of this information, our study aimed to investigate the protective effects of strategies involving vascular stabilization through CB1 receptor antagonism and controlling the immune response through CB2 receptor activation on sepsis-induced organ damage and mortality.

SOME STUDIES THAT HAVE BEEN CONDUCTED

CB1 and CB2 receptors play critical roles in the pathophysiology of sepsis, acting like a double-edged sword. Studies on the relationship between sepsis and cannabinoid receptors have primarily focused on strategies involving CB1 blockade and CB2 activation. Sepsis modeling, often performed in rodents using the Cecal Ligation and Puncture (CLD) method, has shown excessive secretion of endocannabinoids (AEA and 2-AG) and their binding to CB1 receptors in blood vessels, dangerously lowering blood pressure. Studies targeting CB2 receptors on immune system cells (macrophages, neutrophils) have shown more promising results (Güler et al., 2022).

Vascular Collapse and CB1 Receptor Blockade

Septic shock, one of the most critical stages of sepsis, is characterized by uncontrolled vasodilation and hypotension. Studies on rodent models of sepsis have demonstrated the excessive release of anandamide, particularly from macrophages and endothelial cells, during the septic process. The released AEA (Acid-Electronymic Acid) binds to CB1 receptors in vascular smooth muscle, creating a strong vasodilatory effect. A strategy of CB1 receptor antagonism (blockade) reverses this pathological relaxation, resulting in a 30-40% improvement in mean arterial pressure (Batkai et al., 2007). This is a vital step for maintaining tissue perfusion and vascular stabilization.

Immunomodulation and CB2 Receptor Activation

Unlike CB1 receptors, CB2 receptors are primarily concentrated in immune system cells (macrophages, B and T lymphocytes, neutrophils). Activation (agonism) of CB2 receptors is a key strategy for mitigating the cytokine storm in sepsis. CB2 agonists have been found to exert an anti-inflammatory effect by suppressing the nuclear factor kappa B (NF-κB) pathway, reducing the production of pro-inflammatory cytokines (especially TNF-κB and IL-κB) by over 50% (Saroz et al., 2019). Furthermore, EKS modulation increases antioxidant enzyme capacity, thereby limiting tissue damage caused by reactive oxygen species (ROS).

Sepsis-Related Encephalopathy (SAE) and Neuroprotection

Sepsis affects not only systemic organs but also the central nervous system by crossing the blood-brain barrier. Suppression of microglia, resident immune cells in the brain, via CB2 receptors has been reported to reduce neuroinflammation (Xin et al., 2023). This intervention improves quality of survival by minimizing long-term cognitive dysfunction and neuronal damage that may develop after sepsis (Bala et al., 2024). Neuronal epileptic seizures (PAS) are closely associated with long-term cognitive impairment, and their mechanism is complex, including excessive microglial activation and neuroinflammation. In a study where sepsis was induced by CLP, CBR2 receptor activation was shown to be effective in supporting neuronal protection and survival (Yang et al., 2022). The CB2R-specific agonist HU308 may have protective effects against PAE by inhibiting microglial activity and neuronal pyroptosis.

CONCLUSION

Antagonism of CB1 receptors helps control vascular complications of septic shock, while activation of CB2 receptors reduces the risk of systemic inflammatory response and multiple organ failure. This dual and coordinated therapeutic approach provides more comprehensive protection against the heterogeneous nature of sepsis compared to traditional methods. Future clinical trials have the potential to determine the efficacy and safety of these molecular targets in humans, ushering in a new era in sepsis management..

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SCIENTIFIC APPROACHES IN BEEKEEPING, RESEARCH & DEVELOPMENT AND APPLICATION CENTER EXPERIENCES

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Abstract

Beekeeping is not just an agricultural practice but an encompassing field for preservation and sustainability of biological and ecological diversity. Here, research and development efforts on beekeeping addressed with a summary review on modern beekeeping. For this purpose, biological evaluation of honey bee (*Apis mellifera*) with different aspects was laid and scientific and industrial aspects that research centers have a role of discussed with a particular focus on beekeeping production standardization. Diverse array of research revealed that data-based, research-driven frameworks in beekeeping are resulting in particularly significant improvements in both hive health and beekeeping product qualities. Overall, it can be summarized as such that modern beekeeping should transcend tradition-driven practices and embrace research-driven and data-based standardization framework, which can be achieved and facilitated by specialized application and research centers.

Keywords: Beekeeping, *Apis mellifera,* R&D, bee products, biodiversity

ARICILIKTA BİLİMSEL YAKLAŞIMLAR, AR-GE VE UYGULAMA MERKEZİ DENEYİMLERİ

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Özet

Arıcılık; yalnızca bal üretimiyle sınırlı olmayan, ekosistem sürdürülebilirliği, tarımsal verimlilik, biyolojik çeşitlilik ve insan sağlığı açısından stratejik öneme sahip çok yönlü bir tarımsal faaliyettir. Bu bildiri kapsamında, arıcılık alanındaki bilimsel ve uygulamalı çalışmalar çerçevesinde, modern arıcılıkta Ar-Ge temelli yaklaşımlar ele alınmıştır. Özellikle bal arılarının (Apis mellifera) fizyolojisi, bağışıklık sistemi, stres faktörleri, hastalık ve zararlılar, çevresel toksinler ve beslenme ilişkileri biyolojik temelde değerlendirilmiştir. Bunun yanı sıra merkez bünyesinde yürütülen bal, polen, propolis, arı sütü ve arı zehri gibi arı ürünlerinin kalite, biyolojik aktivite ve standardizasyon çalışmalarına yer verilmiştir. Yapılan çalışmaların bulguları, kontrollü koloni yönetimi, bilimsel besleme stratejileri ve bölgesel flora temelli üretim modellerinin hem koloni sağlığını hem de ürün kalitesini anlamlı düzeyde artırdığını göstermektedir. Sonuç olarak, arıcılığın geleneksel bilgi ile sınırlı kalmaması, biyoloji temelli bilimsel veriler ışığında Ar-Ge ve uygulama merkezleri aracılığıyla geliştirilmesi gerektiği vurgulanmaktadır.

Anahtar Kelimeler: Arıcılık, *Apis mellifera*, Ar-Ge, arı ürünleri, biyolojik çeşitlilik

1. Introduction

Limiting the beekeeping to an agricultural practice would be a mistaken assumption as the beekeeping has its undeniable reaches to diverse fields in ecological sustainability, biodiversity conservation, and pharmaceutical research. Accumulated research on honey and other beekeeping products inevitably leads to increased trends in their use for both basic and applied sciences. As ages of old agricultural practice, beekeeping today acknowledged as a principal pillar of ecology since it's clearly known today that the honey bee (*Apis mellifera*) is the cornerstone of continuous production of plant species, having responsible for the pollination of almost 70% of agricultural plant species. In short, the practice of beekeeping is actually a strategic practice for the sustainability of diverse ecosystems.

2. Scientific Approaches in Apiculture

In today's perceived understanding of the modern apiculture, different branches of life sciences are all contributing in a multidisciplinary mode of action. Particularly the fields of molecular biology and biochemistry, microbiology, and ecology are pronounced. Certain approaches are trending in the scientific landscape for modern apiculture, which include hive managements for sustained well-being of honey bees; nutritional optimization frameworks; biological profiling for product improvements; and environmental monitoring for sustainability. These approaches have broad aims including hive preservation, yield optimizations, product profiling, and preserving sustained production.

Today, improvements in molecular methods lead to ready availability of genomic and transcriptomic analyses, which enable findings in honey bee physiology in gene level. Again, microbiome methods enable novel approaches for hive management by revealing aspects of overall health and resilience of particular colonies.

3. Multidisciplinary Nature of Scientific Beekeeping

Modern apiculture that employs scientific approaches utilizes research findings from different fields of life sciences, which particularly encompass molecular biology and biochemistry, biotechnology, pharmacognosy, microbiology, and ecology. These disciplines provide system-level contributions in a hollistic manner for the comprehension and

improvement of vital parameters in apiculture, namely honey bee healthcare, dynamic management of hives and colonies, and environmental susceptibility. Improvements in honey bee health dynamics mainly encompass the immunology of bees, which include immune responses, resistance mechanisms, and stress tolerance. Dynamic management of hives and colonies particularly focuses on data-driven optimization, conservation, and sustainability frameworks. Additionally, disease and pest control—particularly against threats such as Varroa destructor and microbial infections—requires integrated biological and chemical approaches (Evans & Schwarz, 2011; Van Engelsdorp & Meixner, 2010). Also in recent years, factors such as climate change, habitat loss, pesticide use, monoculture farming practices, and pathogen pressure have seriously threatened bee health. The increase in colony losses has clearly shown that beekeeping cannot be sustained with traditional methods. At this point, the integration of biology, molecular ecology, toxicology, microbiology, and nutritional sciences with beekeeping has become essential. Assessments of colony health revealed a strong negative correlation between Varroa destructor density and colony performance. In colonies where scientifically based integrated pest management methods were applied, both overwintering success and spring development were found to increase significantly. Furthermore, it was observed that the indiscriminate use of chemicals puts a strain on the bees' immune system and accelerates colony losses. In feeding studies, it was determined that supplementary feeding with formulations tailored to biological needs during periods of insufficient natural pollen sources increased hypopharyngeal gland development and brood-feeding capacity. In addition, it was found that monotonous sugar-based feeding reduced colony resistance in the long term.

4. Analytical Characterization of Bee Products

Advanced analytical techniques play a critical role in determining the chemical composition and quality of bee products. Various biologically active substances that have diverse functions like phenolic compounds and flavonoids can be assessed and profiled by employing chromatography and spectroscopy methods on both honey and related products. In conjunction with spectroscopy, HPLC (High Performance Liquid Chromatography) and GC-MS (Gas Chromatography – Mass Spectrometry) methods can be utilized to reveal the substance variations in honey, propolis, royal jelly, and bee bread for biochemical profiling, which has close ties with ecological variables that shape bee populations. Therefore, utilization of such methodologies for biochemical fingerprinting and profiling the product integrity enable both authentication protocols and sustained improvements in product qualities (Sforcin, 2016).

5. Evaluation of Biological Activities

Investigations of beekeeping products for their biological activities can be conducted by using in vitro, in vivo, and in silico methodologies. Particular bioactivities like antioxidant, anti-inflammatory, antimicrobial, and anti-tumoral properties are generally assessed by utilizing in vitro methods, whereas in vivo methods are utilized for investigations of substance-driven physiological changes or therapeutic potentials. Molecule-level specialized interactions and their functional predictions are requiring the use of in silico methods, particularly molecular docking strategies and molecular simulation models. All three methodology approaches were used extensively in previous studies conducted on beekeeping products and revealed particularly promising therapeutical potential in such products due to the abundance of flavonoids and phenolic acids (Demirci, 2025; Demir, 2024; Pınar Sur, 2025; Özkan, 2025; Pasupuleti et al., 2017). Such analyzes also pronounced the exceptional nutritional value of beekeeping products while also establishing floral correlations in the variations seen in biological activities (Demirci, 2025; Demir, 2024; Pınar Sur, 2025; Özkan, 2025). Different studies conducting quality analyzes revealed correlations between HMF levels and enzymatic activity of beekeeping products and harvesting time and storage management, which are all clearly emphasizing the standardization and sustainability in beekeeping practices.

6. R&D in Standardization and Quality Control

A solid foundation of research and development (R&D) framework is a strict necessary for streamlined and sustainable beekeeping in today's world since there is a pronounced dependency between quality and environmental variations, which in itself is a justification for deployments of standart procedures. Major efforts in R&D are mostly in product characterization and product utilization. As mentioned before, analytical methodologies, which principally include HPLC, GC-MS, and spectrophotometry assays like QTOF-MS, are widely employed for biochemical profiling approaches, and along with the deployment of traceable biochemical markers for biogeography links such efforts enable solid improvements both in quality and value (Bogdanov et al., 2008). As stated before, biological activities of both products and bioactive substances are widely in study by utilizing both in vitro and in vitro approaches. With the development of more concrete in silico methodologies, including aforementioned molecular docking and simulations, bioactive substances found in beekeeping products are increasingly come into use in pharmaceutical research by investigating specific molecular interactions to reveal potential functions. All in all, studies revealed that bioactive

substances in beekeeping products are providing ample opportunities for novel therapeutic agents and innovative drug discoveries, which strengthen the need for computational studies in multidisciplinary landscape.

7. Molecular Modeling and Drug Design Applications

As already stated, developments in computational biology field enable more capable methodologies that can be utilized for pharmaceutical research, which provide researchers with novel candidates for potential therapeutic agents as seen in molecular modeling and interaction simulation studies. Molecule-level specific target interactions between bioactive substances and potential targets can be analyzed at atomic levels by the deployments of molecular docking approaches. Such studies already revealed solid foundation for the discovery of novel yet natural-substance derived therapeutic agents in pharmaceutical research landscape (Ferreira et al., 2015).

8. The Role of Application and Research Centers

Since theory should transition into practice, and data should drive the course of standardization, specialized institutions dubbed application and research centers are necessary bridges connecting the scientific data with the practice framework. For this connection, the bridge is being built by such centers by reaching out to agricultural practitioners, conducting further research in innovative approaches for industry-relevant circles, and generating value-added inputs into commercial circles. Fundamentally, such institution for beekeeping are places where academic work is blending with the industrial applications in line with close cooperation of laboratory processes and field data drives. Field data drives are what can be summed as the environment-driven data variable in beekeeping, which include hive to colony and hive to product variables. Laboratory processes are where profiling and standardization frameworks are being made into reality.

In more practical terms, these centers are mainly having objectives in following goals: modernization of beekeeping practices; providing framework for beekeeping standardization; conducting industry-relevant research; and driving general practices with data-backed innovations and processes. Overall, these institutions are places for the solid improvements of both production and product quality by enabling the cooperation of different actors that have roles in beekeeping. Accumulated data in the literature emphasizes the significance of such

centers both in applied sciences, particularly for pharmaceutical research, and field practice improvements, particularly for sustainability in production.

9. Conclusion

It can be deducted from the available results that research-based principles and data-driven procedures are significant for the development and advancement of modern beekeeping. Advancement of modern beekeeping principally requires a scientific framework that leads to a solid foundation for beekeeping standardization, which would contribute to basic, applied, and medical sciences and research, but also to general agricultural landscape both regional and global. Contributions and benefits would also extend to ecological preservation and conservation efforts and biogeography sustainability. Therefore, multidisciplinary and industry-relevant research and applications are increasingly necessary, not just for honey or related products but for human nutrition and health. Hence, these needs practically necessitate the existence of well-established, adequately funded institutions specialized in modern beekeeping research and applications, where multidisciplinary research utilizing laboratory and computational methods can be conducted and research data can be translated into field practice. Such institutions are essential for academy to industry translation of scientific research. In the end, these centers for both research and field applications are mainframes of sustained production and standardization frameworks that are vital for today's modern beekeeping industry and all the related fields that would use beekeeping products.

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ANTI-INFLAMMATORY EFFECTS OF GOJI BERRY (*Lycium barbarum*) EXTRACTS FROM THE PROVINCE OF SİVAS

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Abstract

The aim of this study was to determine the *in vitro* anti-inflammatory activities of extracts of goji berry (*Lycium barbarum*) fruits collected from the central and Sarkısla districts of Sivas province, prepared with five different solvents and three different concentrations, using the albumin denaturation inhibition test. Fruit samples were extracted with ethyl acetate, ethanol, methanol, chloroform, and aqueous solvents. The obtained extracts were subjected to bovine serum albumin (BSA) denaturation inhibition tests at concentrations of 100 mg/ml, 10 mg/ml, and 1 mg/ml. Diclofenac sodium was used as a positive control. Data were statistically analyzed using two-way ANOVA. In both localities, the highest inhibition activity was observed in the ethyl acetate extract. In the central samples, ethyl acetate at a concentration of 100 mg/ml achieved an inhibition value of 52.93 ± 2.05%. The lowest inhibitory activity was determined for chloroform at 19.83 ± 0.64%. In Şarkışla samples, ethyl acetate at a concentration of 100 mg/ml achieved an inhibitory value of 56.93 ± 1.45. The lowest inhibitory activity was determined in the aqueous solvent at 18.96 ± 0.98. The solvent-concentration interaction was also found to be statistically significant for both localities ($p<0.0001$). It was observed that goji berry fruit, especially its ethyl acetate extract, exhibited significant anti-inflammatory potential. These findings indicate that *L. barbarum* fruit can be evaluated in studies on the development of natural anti-inflammatory agents.

Keywords: *Lycium barbarum*, Goji berry, Anti-inflammatory activity, Albumin denaturation inhibition, Sivas.

SİVAS İLİ GOJİ BERRY (*Lycium barbarum*) EKSTRAKTLARININ ANTİİNFLAMATUVAR ETKİLERİ

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Özet

Bu çalışmanın amacı, Sivas ili Merkez ve Şarkışla ilçelerinden toplanan goji berry (*Lycium barbarum*) meyvelerinin beş farklı çözgen ve üç farklı konsantrasyonda hazırlanan ekstraktlarının *in vitro* antiinflamatuvar aktivitelerinin albümin denatürasyon inhibisyon testi ile belirlenmesidir. Meyve örnekleri etil asetat, etanol, metanol, kloroform ve su çözgenleri ile ekstrakte edilmiştir. Elde edilen ekstraktlar 100 mg/mL, 10 mg/mL ve 1 mg/mL konsantrasyonlarında bovin serum albümini (BSA) denatürasyon inhibisyon testine tabi tutulmuştur. Pozitif kontrol olarak diklofenak sodyum kullanılmıştır. Veriler iki yönlü ANOVA ile istatistiksel olarak analiz edilmiştir. Her iki lokalitede de en yüksek inhibisyon aktivitesi etil asetat ekstraktında gözlenmiştir. Merkez örneklerinde etil asetat 100 mg/mL konsantrasyonda %52.93 ± 2.05 inhibisyon değerine ulaşılmıştır. En düşük inhibisyon aktivitesi kloroform %19.83 ± 0.64 olarak belirlenmiştir. Şarkışla örneklerinde etil asetat 100 mg/mL konsantrasyonda 56.93 ± 1.45 inhibisyon değerine ulaşılmıştır. En düşük inhibisyon aktivitesi su çözgeninde 18.96 ± 0.98 olarak belirlenmiştir. Çözgen-konsantrasyon etkileşimi de her iki lokalite için istatistiksel olarak anlamlı bulunmuştur ($p<0.0001$). Goji berry meyvesinin özellikle etil asetat ekstraktının kayda değer antiinflamatuvar potansiyel sergilediği gözlenmiştir. Bu bulgular, *L. barbarum* meyvesinin doğal antiinflamatuvar ajan geliştirme çalışmalarında değerlendirilebileceğini göstermektedir.

Anahtar Kelimeler: *Lycium barbarum*, Goji berry, Antiinflamatuvar aktivite, Albümin denatürasyon inhibisyonu, Sivas

1. Introduction

Inflammation is a protective response of the organism against tissue damage or pathogen invasion, but when it becomes chronic, it plays a central role in the development of many pathological conditions such as cardiovascular diseases, diabetes, cancer, and neurodegenerative disorders (Yacine et al., 2025). Nonsteroidal anti-inflammatory drugs (NSAIDs), commonly used today in the treatment of inflammatory diseases, are effective, but their long-term use is associated with gastrointestinal, cardiovascular, and renal side effects. This situation necessitates the search for safer and more effective anti-inflammatory agents (Ghlichloo and Gerriets, 2023). Plant-based sources play an important role in the development of alternative anti-inflammatory agents due to their rich phytochemical content. *Lycium barbarum L.,* commonly known as "wolfberry" or "goji berry," is an important medicinal plant that has been used in traditional medicine for centuries. The fruits of this plant have a rich phytochemical profile, containing polysaccharides, carotenoids, flavonoids, and vitamins. Studies have shown that goji berries exhibit antioxidant, immunomodulatory, antitumor, hepatoprotective, and neuroprotective activities (Hu et al., 2025).

Protein denaturation is a critical component of the inflammatory process. Reactive oxygen species and other mediators produced under inflammatory conditions disrupt the structural integrity of tissue proteins, leading to denaturation. This process contributes to the amplification of the inflammatory response and the progression of tissue damage. Therefore, agents that can prevent protein denaturation are considered to have potential anti-inflammatory activity (Forrester et al., 2018).

Goji berry cultivation has become widespread in Türkiye in recent years, especially in the Central Anatolia Region, with Sivas province being one of the production areas. However, scientific data on the biological activity of goji berry samples collected from this region are limited. The aim of this study was to evaluate the *in vitro* anti-inflammatory potential of extracts of goji berry fruits collected from the central and Şarkışla districts of Sivas province, prepared with solvents of different polarities, using the albumin denaturation inhibition test, and to comparatively analyze the effect of the extraction solvent on the activity.

2. Material and Methods

2.1. Plant Material and Extraction

The goji berry (*L. barbarum*) fruits used in the study were collected from the Central district and Şarkışla district of Sivas province in 2023-2024. Dried and ground fruit samples were extracted using ethyl acetate, ethanol, methanol, chloroform, and aqueous as solvents. The extraction process was carried out by maceration at room temperature with an appropriate solvent/sample ratio. After filtering the obtained extracts, the solvents were removed under appropriate conditions, and the dry extracts were stored at -20°C. For biological activity tests, extracts were prepared by dissolving them in dimethyl sulfoxide (DMSO) at concentrations of 100 mg/mL, 10 mg/mL, and 1 mg/mL.

2.2. Albumin Denaturation Inhibition Test

Albumin denaturation inhibition test was used to evaluate anti-inflammatory activity. In the experiment, a 5% (w/v) bovine serum albumin (BSA, Capricorn Scientific) solution was used as the protein source. A reaction mixture was prepared in each well to have a total volume of 200 µL (100 µL 5% BSA solution, 78 µL phosphate buffer solution (PBS, pH 6.3, Biomatik), 20 µL test extract (or DMSO for control), 2 µL 1N hydrochloric acid (HCl)). The negative control group was prepared to contain only PBS and DMSO, while the blank sample was created from albumin and phosphate buffer. Diclofenac sodium, a nonsteroidal anti-inflammatory drug known as a positive control, was used at the same concentrations. The prepared microplate was incubated at 37°C for 20 minutes to induce protein-active substance interaction. Following incubation, the plate was heated to 70°C for 5 minutes to induce protein denaturation. The samples were then allowed to cool at room temperature for approximately 10 minutes. The turbidity that occurs after the reaction was considered an indicator of protein denaturation, and absorbance measurements were performed at a wavelength of 660 nm using a BMG Labtech Spectrostar Nano microplate reader (Williams et al., 2008).

2.3. Calculating the Inhibition Percentage

The percentage of protein denaturation inhibition was calculated using the following formula, where Acontrol represents the absorbance of the negative control group and Atest represents the absorbance value of the test samples.

$$\text{Percentage inhibition (\%)} = \frac{\text{Absorbance of control} - \text{Absorbance of test}}{\text{Absorbance of control}} \text{X } 100$$

2.4. Statistical Analysis

All experiments were performed in triplicate, and results are expressed as mean ± standard deviation. The effects on the percentage of inhibition were calculated using the bioRender Graph module.

3. Results

3.1. Anti-inflammatory Activity of Central Samples

The albumin denaturation inhibitory activities of various solvent extracts of goji berries collected from the centre are presented in Table 1 and Figure 1.

Table 1. Inhibition percentages of goji berry extracts collected from the center

Extract / Control	100 mg/mL (%)	10 mg/mL (%)	1 mg/mL (%)
Diclofenac Sodium*	80.03 ± 0.70	66.86 ± 1.28	60.66 ± 0.32
Ethyl Acetate	52.93 ± 2.05	49.90 ± 0.72	44.56 ± 0.77
Ethanol	49.23 ± 0.40	45.33 ± 0.60	38.70 ± 0.40
Methanol	32.20 ± 1.87	26.40 ± 1.22	17.50 ± 6.42
Chloroform	19.83 ± 0.64	16.06 ± 1.79	18.03 ± 4.70
Aqueous	21.16 ± 0.65	17.93 ± 0.55	17.33 ± 4.92

* Positive control

In the samples from the central district, ethyl acetate extract showed the highest inhibition value (52.93 ± 2.05%), followed by ethanol, methanol, aqueous, and chloroform extracts.

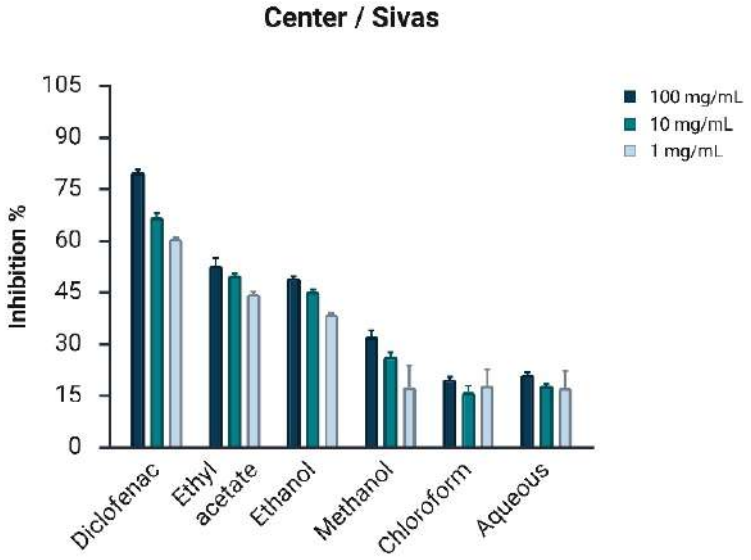


Figure 1. Inhibition percentages of the center at different concentrations (Created in https://BioRender.com)

3.2. Anti-inflammatory Activity of Plant Extracts from Şarkışla District

The albumin denaturation inhibition activities of different solvent extracts of goji berry fruits collected from Şarkışla district are presented in Table 2 and Figure 2.

Table 2. Inhibition percentages of goji berry extracts collected in Şarkışla district

Extract / Control	100 mg/mL (%)	10 mg/mL (%)	1 mg/mL (%)
Diclofenac Sodium*	80.03 ± 0.70	66.86 ± 1.28	60.66 ± 0.32
Ethyl Acetate	56.93 ± 1.45	52.10 ± 1.67	50.33 ± 0.87
Ethanol	50.70 ± 0.55	49.46 ± 0.86	32.40 ± 1.94
Methanol	48.30 ± 0.40	44.70 ± 0.81	38.76 ± 0.83
Chloroform	23.66 ± 2.65	17.73 ± 0.65	15.00 ± 0.65

Aqueous	18.96 ± 0.98	15.30 ± 0.2	14.20 ± 0.79

*Pozitif kontrol

In the Şarkışla samples, the highest inhibition activity was observed in the ethyl acetate extract, reaching a value of 56.93 ± 1.45 at a concentration of 100 mg/mL. This value was followed by ethanol (50.70 ± 0.55), methanol (48.30 ± 0.40), chloroform (23.66 ± 2.65), and aqueous (18.96 ± 0.98) extracts. The positive control, diclofenac sodium, showed 80.03 ± 0.70% inhibition at the same concentration.

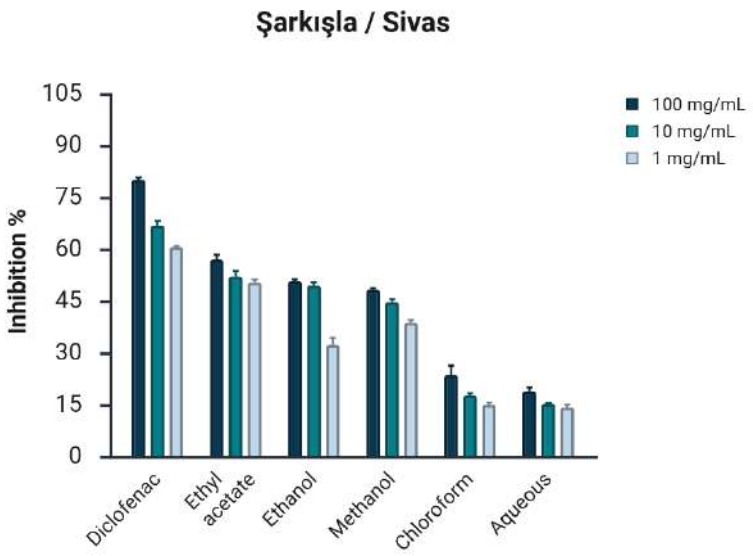


Figure 2. Inhibition percentages of Şarkışla district at different concentrations (Created in https://BioRender.com)

According to the two-way ANOVA results, the solvent-concentration interaction was found to be statistically significant for both localities ($p<0.0001$).

4. Discussion and Conclusion

In this study, the *in vitro* anti-inflammatory activities of goji berry extracts prepared with different solvents from the central and Şarkışla districts of Sivas province were evaluated using the albumin denaturation inhibition test. Our findings reveal that ethyl acetate extracts, in particular, exhibit significant anti-inflammatory potential. The fact that the ethyl acetate extract showed the highest activity can be attributed to this solvent's capacity to effectively extract bioactive compounds of medium polarity. Given the rich phytochemical content of goji berries

in terms of flavonoids, phenolic acids, and carotenoids, ethyl acetate is thought to extract a significant portion of these compounds. Literature reports that flavonoids and phenolic compounds are effective in preventing protein denaturation (Thida et al., 2024; Jangga et al., 2025).

It is also noteworthy that the ethanol extract shows activity similar to that of ethyl acetate. Ethanol is considered a safe solvent in the food and pharmaceutical industries, suggesting that ethanol extracts may be advantageous in terms of potential applications (Plaskova and Mleck, 2023). The relatively low activity of chloroform and aqueous extracts indicates that the compounds responsible for the anti-inflammatory effect are not adequately extracted with these solvents. Chloroform, being a nonpolar solvent, primarily extracts lipids and nonpolar compounds, while aqueous extracts polar polysaccharides and glycosides (Saini et al., 2021). These findings indicate that the active compounds have intermediate polarity. The observation of similar activity profiles in both localities indicates that geographical variation does not create a significant difference in these examples. However, studies with larger sample groups will allow for a more detailed assessment of the locality effect. Statistical analyses revealed that both solvent type and concentration had a significant effect on the inhibitory activity. The significant solvent-concentration interaction indicates that different extracts responded differently to changes in concentration. Diclofenac sodium, used as a positive control, showed higher activity than the plant extracts at all concentrations. However, the fact that the ethyl acetate extract reached approximately 66% of the activity of diclofenac sodium at the highest concentration highlights the potential therapeutic value of this extract.

The albumin denaturation inhibition test is a reliable and widely used *in vitro* method for preliminary screening of anti-inflammatory activity. Protein denaturation plays a significant role in inflammatory processes and constitutes one of the mechanisms of action of anti-inflammatory drugs. Therefore, it is thought that extracts showing high activity in this test may also have the potential for anti-inflammatory effects under *in vivo* conditions. In conclusion, ethyl acetate and ethanol extracts of goji berries collected from Sivas province exhibited significant anti-inflammatory activity in the albumin denaturation inhibition test. These findings suggest that *L. barbarum* berries can be considered a potential resource in studies on the development of natural anti-inflammatory agents. Future studies are recommended to isolate and characterize the active compounds, apply different *in vitro* anti-inflammatory tests, and evaluate their *in vivo* activity.

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KEY DATA SOURCES AND ANALYSIS TOOLS USED IN NETWORK PHARMACOLOGY FOR DRUG DISCOVERY

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Abstract

Cancer, Alzheimer's, Parkinson's, diabetes and cardiovascular diseases affect numerous molecular pathways. Researchers have attempted to develop treatment methods by identifying the enzyme or receptor thought to cause the disease and designing target-specific compounds. Although this approach has yielded positive results in the treatment of many diseases, it has been found to be insufficient for the treatment of chronic and complex diseases over time. Because modulation of a single target has often proved insufficient in the clinic to affect the entire disease process. Consequently, new treatment strategies have been identified and drug designs initiated. Systems biology is a multidisciplinary scientific approach that examines the multi-layered and interactive structure of biological components such as genes, proteins, and cells found in living organisms, enabling a holistic understanding of how they interact and function together in complex processes. As cellular processes dynamically progress from genes to proteins and then to the metabolite level, systems biology-based approaches have gained importance in drug discovery processes. Network pharmacology (NP) is an interdisciplinary field at the heart of modern drug discovery, using network models to analyse interactions between genes, proteins, diseases, and drugs through systems biology. NP explains the molecular targets of candidate compounds and the functional relationships between these targets, thereby attempting to elucidate the mechanisms through which a compound may exert its effects on a disease. Synthetic chemicals form the basis of the modern pharmaceutical industry in drug discovery. Secondary metabolites found in plant drugs also enable network-based analyses to elucidate the biological pathways involved in a disease's mechanism. This paper will discuss databases such as TCMSP, IMPPAT, DisGeNET, GeneCards, STRING, DrugBank, and PubChem which are used in drug discovery in NP. It will explain what data these databases provide to users and for what purposes they are used. It will also discuss the applications and limitations of computational tools and software such as Cytoscape, Metascape, AutoDock, and Maestro. This paper will outline the capabilities offered to users by the databases and software to be used in plant-based drug development studies in NP.

Keywords: Network pharmacology, Systems Biology, Drug Discovery, Databases

NETWORK FARMAKOLOJİDE İLAÇ KEŞFİ İÇİN KULLANILAN TEMEL VERİ KAYNAKLARI VE ANALİZ ARAÇLARI

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Özet

Kanser, alzheimer, parkinson, diyabet ve kardiyovasküler hastalıklar, çok sayıda moleküler yolağı etkilemektedir. İlaç keşiflerinde geleneksel yaklaşım "tek ilaç-tek hedef" şeklindedir. Araştırmacılar hastalığa neden olduğu düşünülen enzim veya reseptörü belirleyip, hedefe özgü bileşik tasarımı yaparak tedavi yöntemleri geliştirmeye çalışmışlardır. Bu yaklaşım, birçok hastalığın tedavisinde olumlu sonuçlar vermesine rağmen zamanla kronik ve kompleks hastalıkların tedavisi için yetersiz kaldığı keşfedilmiştir. Çünkü tek bir hedefin modülasyonu, hastalık sürecinin tamamını etkilemede klinikte çoğu zaman yetersiz kalmıştır. Bunun üzerine yeni tedavi stratejileri belirlenip ilaç tasarımları yapılmaya başlanmıştır. Sistem biyolojisi, canlının yapısında bulunan gen, protein ve hücre gibi biyolojik bileşenlerin çok katmanlı ve etkileşimli yapısını inceleyerek, karmaşık süreçlerde birlikte nasıl etkileşime girdiği ve nasıl çalıştığını bütüncül bakış açısıyla anlamayı sağlayan multidisipliner bilim yaklaşımıdır. Hücresel işleyiş genlerden proteinlere sonrada metabolit düzeyinde dinamik şekilde ilerlediği için, ilaç keşif süreçlerinde sistem biyolojisi temelli yaklaşımlar önem kazanmıştır. Network farmakoloji (NF), sistem biyolojisi ile gen, protein, hastalık ve ilaç etkileşimlerini ağ modelleri ile analiz eden modern ilaç keşfinin merkezinde bulunan disiplinler arası bir alandır. NF ilaç adayı olacak bileşiklerin moleküler hedeflerini ve bu hedeflerin birbirleriyle olan işlevsel ilişkilerini açıklayarak, bir bileşiğin bir hastalık üzerinde hangi mekanizmalar aracılığıyla etki edebileceğini açıklamaya çalışır. İlaç keşiflerinde sentetik kimyasal maddeler modern farmasötik endüstrinin temelini oluşturur. Bitkisel droglarda bulunan sekonder metabolitler de ilaç tasarımlarında ağ temelli analizler ile bir hastalığın mekanizmasındaki biyolojik yolakları açıklanmasına imkân sunar. Bu bildiride, NF'de ilaç keşiflerinde kullanılan TCMSP, IMPPAT, DisGeNET, GeneCards, STRING, DrugBank, PubChem gibi veri tabanlarından bahsedilecektir. Bu veri tabanlarının hangi verileri kullanıcılara sunduğu ve hangi amaçlarla kullanıldığı açıklanacaktır. Aynı zamanda Cytoscape, Metascape, AutoDock ve Maestro gibi hesaplamalı araç ve yazılımların kullanım alanları ve sınırlamalarından bahsedilecektir. Bu bildiri ile NF'nin bitkisel kaynaklı ilaç geliştirme çalışmalarında kullanılacak olan veritabanları ve yazılımların kullanıcılara sunduğu imkânlar belirtilecektir.

Anahtar Kelimeler: Network farmakoloji, Sistem Biyolojisi, İlaç Keşfi, Veri Tabanları

1. Introduction

Instead of the traditional "one drug-one target-one disease" approach, modern medicine and drug discovery processes prefer a more holistic approach that understands complex diseases at the systemic level (Casas et al., 2019). In multifactorial diseases such as cancer, diabetes, and neurodegenerative diseases, traditional methods may be insufficient for treatment because the cause is often dysfunction of the entire regulatory network rather than a single gene mutation (Wang et al., 2021). In response to this need, Network Pharmacology (NP) has emerged as an interdisciplinary research field formed by the integration of systems biology, omics technologies, and computer science (Chandran et al., 2017). NP integrates genomic, proteomic, metabolomic, and bioinformatic data to holistically analyze the relationships between drugs, target proteins, disease genes, and biological pathways. In this way, by moving beyond single goals, the relationships between multiple goals and mechanisms become understandable. This method rejects the notion that drugs interact with only a single target protein, instead basing itself on the principle that a drug can act on multiple targets within a complex biological system, or that different drugs can affect the same target. NP, an *in silico* approach, builds a bridge between traditional medicine and modern pharmacology by establishing "protein-compound/disease-gene" networks. (Li and Kar, 2025). In this context, reliable, open-access databases and advanced computerized analysis platforms form the backbone of network pharmacology. This manuscript supports knowledge about the databases and software used by NP in its plant-based drug researches.

2. Databases

2.1. TCMSP (Traditional Chinese Medicine Systems Pharmacology Database)

TCMSP is a very succesfull database and research platform that correlate the bridges between Traditional Chinese Medicine (TCM) and modern pharmacology. The TCMSP presents detailed data on medicinal plants used in Chinese medicine, their chemical contents, the biochemical targets these components interact with, and targeted diseases. In addition it provides pharmacokinetic parameters of a plant-derived compound to become a medicine. These parameters supports information like oral bioavailability (OB), drug-likeness (DL), and blood-brain barrier (BBB) permeability. These qualities give permission for the developing of how the components are absorbed, distributed, metabolized, and excreted in the body (ADME).

Researchers are using this platform to know the complex mechanisms of herbal drugs at the systems level and to define new therapeutics (Ru et al., 2014).

2.2. IMPPAT (Indian Medicinal Plants, Phytochemistry and Therapeutics)

It is a very important digital database that connects plants derived resources like phytochemicals from Indian medicine (Ayurveda), and the biochemical targets with which these contents related in cell level. By integrating ethnobotanical data from traditional Ayurvedic, Siddha, and Unani texts with current and widespread cheminformatic tools (such as ADMET profiles, Lipinski rules, and 3D structural models). The researchers have opportunities to process plant-compound-target protein relationships. The cytoscape software is integrated into this database interface. And cytoscape tool let the users to interactively visualize and present plant-phytochemical-disease networks. The very important qualification of this programme can summarize as follows: the users can also analysis by plant name, or perform similarity searches by entering chemical structures in SMILES format (Monharaj et al., 2018).

2.3. DisGeNET

DisGeNET is a very special application platform that supports information about genes and variants associated with human diseases. It presents very critical data source in NP studies, particularly for establishing disease-gene-drug networks and determining therapeutic targets. It is used to define therapeutic targets of the plants' compound and show which diseases it is related with. To fictionalize the "natural product–target–disease" triangle is very essential, and data can be transformed to Cytoscape or Metascape for network visualization with the easily and quickly protocols (Piñero et al., 2017).

2.4. GeneCards

This is an user friendly database processing the human genes and their connections with different diseases. The GeneCards application provides researchers to obtain gene descriptions, expression levels, protein products, and disease links. In NP studies, the first aim is to understand disease-associated genes and evaluate their functional characteristics. The GeneCards application uses the conjunction with other disease databases like OMIM, to support the standardize gene-disease relationships. This integration provides the identification of

overlapping genes between drug targets and disease targets in network pharmacology workflows (Stelzer, 2016).

2.5. STRING (Search Tool for the Retrieval of Interacting Genes/Proteins)

It is a widespread and current bioinformatics platform for the analyze the systematically study protein-protein interactions (PPIs) in biological systems. The String database is launched in 2000, and this platform has been continuously updated and expanded to include data from over 14,000 different types. It reports functional connections between proteins. It obtains laboratory-produced data, computational predictions, text mining, and curated databases. In NP research, it is evaluated a fundamental tool, particularly for understanding disease mechanisms and analyzing the effects of drugs at the protein network level (Szklarczyk et al., 2025).

2.6. DrugBank

The DrugBank is a curated online database presenting comprehensive knowledge on drug qualifications and properties, drug targets, and pharmacogenomic interactions, used in both research and clinical practice. This toll is launched in 2006, and this platform is predicted a fundamental resource for understanding system-level drug-target-disease interactions in NP researches. The DrugBank builts the bridges between traditional drug discovery and modern network pharmacology, supporting precision medicine practices and plant-based drug development processes with systematic data (Knox et al., 2024).

2.7. PubChem

The PubChem is very user friendly and widespread comprehensive, open-access public database managed by the National Center for Biotechnology Information (NCBI) that obtaines knowledge on chemical substances and their biological activities. NPs act as a fundamental infrastructure in modern drug discovery processes, particularly in the stages of compound identification, structural data acquisition, and data mining. Chemical identifiers in SMILES or SDF format obtained from PubChem are used for ligand preparation in AutoDock or Maestro software (Kim et al., 2016).

3. Analysis and Visualization Softwares

3.1. Cytoscape

The cytoscape is a current open-source and user friendly fundamental software platform used for visualizing and analyzing biological pathways and biochemical interaction networks in NP analysis studies. The software is a vital tool for visualizing drug-target, protein-protein (PPI), and gene-disease networks to determine the complex relationships between genes, proteins, drugs, and diseases at the system level. The explaining of “compound-target-disease” networks is used for centrality analysis (degree, betweenness, closeness), “module” detection (with extensions like MCODE and ClusterONE), and statistical measurement of topological parameters. On the other hand, some plugins such as STRINGApp (PPI integration), ClueGO/CluePedia (GO and KEGG enrichment), and CytoHubba (hub gene analysis) give chance to enable data source visualization and interactive network analysis linked to the literature (Shannon et al., 2003).

3.2. Metascape

The Metascape software evaluates the lists of genes or proteins collected by researchers, identifying which biological processes, functions, and pathways those lists focus on. The Gene Ontology (GO) and KEGG (Kyoto Encyclopedia of Genes and Genomes) tools are particularly frequently preferred for pathway enrichment analyses. This programme is used to determine and explain the mechanisms of action of compounds or plant-based ingredients at the systemic level. The analysis results provide scientific data revealing which signaling pathways (e.g., pathways related to cancer or inflammation) a compound affects. The Metascape, in particular, is a key tool that plays a critical role in the “deriving biological meaning from gene lists” stage of the NP workflow. It is also give opportunities enabling the visualisation and functional interpretation of data (Zhou et al., 2019).

3.3. AutoDock and AutoDock Vina

The AutoDock and AutoDock Vina are fundamental current molecular docking tools used in NP analysis to structurally validate the interactions of candidate compounds with target proteins. These tools play an very essential and vital role in bridging the gap between traditional medicine and modern pharmacology by simulating "drug-target" interactions. AutoDock 4 is

programmed to design and predict the binding modes of small molecules to receptors with known 3D structures. The AutoDock Vina is an advanced and applied version, widely validated for small molecule-protein interactions. The AutoDock Vina programme optimizes grid calculations, making the process faster and more accurate in very fast calculations. In the NP workflow, these tools are used to validate whether the "hub" genes or proteins identified in the network analysis actually physically interact with the plant components. The scientist working on this field consider the binding energy and docking scores obtained in this process as the main criteria for prioritizing candidate components (Morris et al., 2009; Trott and Olson, 2010).

3.4. Maestro (Schrödinger Molecular Modeling Suite)

Maestro is an advanced computer-aided drug design (CADD) platform used to structurally validate data obtained in NP studies. The program offers an advanced molecular modeling infrastructure widely used in molecular docking, pharmacophore modeling, molecular dynamics simulations, and virtual screening studies. Thanks to its user-friendly graphical interface, it provides researchers with an integrated working environment that enables them to perform comprehensive *in silico* analyses. Due to its powerful algorithms, high prediction accuracy, and versatile modules, Maestro is frequently preferred in pharmaceutical research, structural biology, and network pharmacology-based drug discovery studies. In molecular docking studies, Maestro includes advanced modules such as Glide, LigPrep, Protein Preparation Wizard, Prime, and Desmond. The current version (2024.06) of the platform developed by Schrödinger is used in multi-target and network-based drug design studies. Compared to AutoDock, it can provide higher accuracy in calculating binding energies; and the dynamic stability of protein-ligand complexes can be evaluated in detail through Glide, Prime MM-GBSA, LigPrep and Desmond modules (Schrödinger Release 2026-2).

4. Conclusion

NP is a holistic approach that is transforming modern drug discovery processes. The success of this system depends on the synchronized use of reliable databases and the right analytical software. TCMSP, IMPPAT, DisGeNET, GeneCards, STRING, DrugBank, and PubChem present the biological, chemical, and clinical dimensions of data, while Cytoscape, Metascape, AutoDock, and Maestro transform this information into a meaningful biological network structure. By integrating these tools, researchers can visualize the system-wide effects of a compound. This enables it to contribute both to the development of new multi-target drugs and

to the repositioning of existing drugs. Finally, the combination of applied and advanced database sequentially for evaluating the data sets, high-resolution molecular modeling technologies and AI-powered algorithms technologies are expected to rapidly transform drug discovery processes in network pharmacology in the early future period.

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ISI VE SICAKLIK KONUSUNUN ÖĞRETİMİ İÇİN BİR EĞİTSEL OYUN TASARIMI

AN EDUCATIONAL GAME DESIGN FOR TEACHING THE TOPIC OF "HEAT AND TEMPERATURE"

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ÖZET

Fen bilimleri konularından 'Isı ve sıcaklık' öğrencilerin öğrenmede güçlük çektiği konulardan biridir. Isı ve sıcaklık, konu ve kavramlarına ait bilgi eksikliği ve kavram yanılgılarıyla da çokça karşılaşılmaktadır. Öğrenmenin zorlaştığı durumlarda ise öğrencilerin derse olan ilgileri azalmakta ve olumsuz etkilenmektedir. Bu durumun ortaya çıkmaması için farklı öğrenme stratejilerinin denenmesi öğrencilerin derse olan motivasyonunu ve ilgisini artırabilmektedir. Oyun temelli fen öğretimi, öğrencilerin eğlenerek öğrenmesini sağlarken, derse olan ilgilerini arttırmaktadır. Öğrencilerin sürecin içinde oynayarak öğrenmesi sağlanırken, oyun oynayan öğrenciler düşünme, uyum, hafıza, uygulama ve bedenini kontrol altına alabilme becerilerini geliştirmektedir. Dolayısıyla, fen bilimleri konuları için hazırlanmış oyunların uygulandığı dersler, öğrencilerin aktif katılımının sağlandığı, ders içinde karşılaşılan problemlerin en aza indirilmesini sağlayabilmektedir. Yürütülen bu çalışmada, 5. sınıf Fen Bilimleri dersi 'Maddenin Doğası' ünitesi 'Isı ve Sıcaklık' konusunun öğretimi için 'ISıcaklık Koşturmacası' isimli eğitsel bir oyun tasarlamak amaçlanmıştır. Bu amaç doğrultusunda çalışma tasarım temelli araştırma yöntemiyle oluşturulmuştur. Tasarım temelli araştırma yöntemi öğrenme biçimlerini ve onları destekleyecek araçları inceleyerek alana özgü tasarımların oluşturulmasını olanak sağlar. Oryantring mantığıyla geliştirilen oyun tasarımının, öğrencilerin konuyu daha kolay anlamalarını ve öğrenme sürecine etkin bir biçimde katılarak öğrenmeyi zevkli bir deneyime dönüştürmelerini destekleyeceği öngörülmektedir. Araştırma sonunda, tasarım sürecindeki deneyimlere de dayalı olarak ilgililere gerekli önerilerde bulunulmuştur.

Anahtar Kelimeler: Isı ve Sıcaklık, Fen öğretimi, Oyun Tasarımı, Eğitsel Oyun

ABSTRACT

Among science subjects, "Heat and Temperature" is one of the topics that students have difficulty learning. Lack of knowledge and misconceptions related to the concepts of heat and temperature are also frequently encountered. In situations where learning becomes difficult, students' interest in the lesson decreases and is negatively affected. To prevent this situation, trying different learning strategies can increase students' motivation and interest in the lesson. Game-based science teaching not only enables students to learn while having fun but also increases their interest in the lesson. While students learn by playing within the process, those who play games develop skills such as thinking, adaptation, memory, application, and controlling their bodies. Therefore, lessons in which games prepared for science topics are implemented can ensure active student participation and minimize problems encountered during the lesson. In this study, it was aimed to design an educational game named "Heat-Temperature Rush" for teaching the topic of "Heat and Temperature" in the "Nature of Matter" unit of

the 5th grade Science course. For this purpose, the study was designed using the design-based research method. The design-based research method enables the creation of domain-specific designs by examining learning styles and the tools that support them. It is anticipated that the game design developed with an orienteering logic will support students in understanding the topic more easily and transforming learning into an enjoyable experience by actively participating in the learning process. At the end of the research, necessary recommendations were made to the relevant stakeholders based on the experiences gained during the design process.

Keywords: Heat and Temperature, Science teaching, Game design, Educational game

GİRİŞ

Teknolojik ilerlemelerle birlikte hızla dönüşen bilim dünyasında, toplumların hem saygınlık kazanması hem de refah düzeyini artırması açısından fen eğitimi önemli bir yere sahiptir. Fen eğitimi, dünyayı anlamaya yardımcı olan bir düşünme yöntemi olarak ele alınmalıdır. Ayrıca bireylere yaşam için gerekli bilgi ve becerileri kazandırmayı ve bu kazanımların yaşamın her aşamasında kullanılmasını hedeflemesi bakımından toplumsal bir boyut içermektedir (Cansüngü, 2000). Etkili bir fen eğitimi ise insan bilgisinin temelini oluşturan kavramlar üzerinden yürütülmelidir. Öğrencilerin kavramları öğrenme sürecinde, zihinlerinde önceden oluşturdukları ilk bilgilerin, başka bir ifadeyle ön kavramların, belirleyici bir rolü bulunmaktadır. Özellikle fen eğitiminde, öğrencilerin öğrenmelerini büyük ölçüde etkileyen bu ön kavramların belirlenmesi, kapsamlı bir araştırma alanı olarak ele alınmaktadır (Griffiths vd.,1988). Ausubel bu konunun önemini: "Etkileyici fen eğitiminin en önemli faktörü öğrencinin daha önce bildiklerinin tespiti, bunun doğrusunun araştırılması ve o doğrultuda ona öğretilmesidir" şeklinde vurgulamıştır (Akt. Cleminson, 1990). Öğrencilerin bilimsel kavramlara yönelmesini sağlamak, onların mevcut kavram yanılgılarının fark edilmesi ve bu yanılgıların öğretim sürecinde ele alınmasıyla mümkün olmaktadır (Eisen & Stavy, 1992). Bu kavramların ve kavramlar arasındaki ilişkilerin ilköğretim düzeyinde doğru öğrenilmemesi, ilerleyen yıllarda karşılaşılacak yeni kavramların da doğru olarak öğrenilmesine engel oluşturmaktadır. Öğrencilerin zihinlerinde oluşturdukları tanımlar ve anlamaların bilimsel yönden kabul edilemeyen durumlar kavram yanılgıları olarak adlandırılır (İnel Ekici, 2016). Fen bilimlerindeki konu ve kavramlar günlük yaşamda sıklıkla karşımıza çıkmaktadır. Öğrencilerin zihinlerindeki temel fen kavramlarını doğru bir şekilde yapılandırmak gelecekte bu kavramların öğretiminde meydana gelebilecek aksaklıkları ortadan kaldırmak için önemlidir. Fen eğitimi literatürüne bakıldığında, kavram yanılgılarının belirlenmesi için birçok çalışmanın olduğu, yapılan araştırmalar incelendiğinde ısı ve sıcaklık konusunun sıklıkla ele alındığı görülmektedir. Çünkü, hayattaki olayları anlamamızı sağlayan kavramlardan olan ısı ve sıcaklık kavramları günlük yaşamda veya informal öğrenme ortamlarında çok sık karşılaşılan kavramlardır (Sontay ve Karamustafaoğlu, 2018). Karamustafaoğlu vd. (2004) çalışmalarında ısı ve sıcaklık kavramlarının öğrencilerin zihinlerinde yapılanmasına yönelik olarak farklı seviyedeki öğrencilerin hatalı fikirler taşıdıklarını göstermiştir. Aydoğan vd. (2003) ısı ve sıcaklık konusundaki öğrencilerin kavram yanılgılarını belirlemiştir. Madu ve Orji (2015) çalışmasında, günlük yaşamda ısı ve sıcaklık kavramlarının tam anlamıyla öğrenilmeden kullanılmasının değiştirilmesi zor olan bir kavram kargaşasına ya da yanılgısına sebep olduğunu ifade etmişlerdir. Günümüzde geleneksel öğretim yöntemlerinin yerini öğrenme sürecini daha verimli ve eğlenceli hâle getirmeyi amaçlayan ve teknolojiden yararlanan yenilikçi yaklaşımların almaya başladığı görülmektedir. Son yıllarda eğitim alanında yaygınlık kazanan bu yenilikçi yaklaşımlar arasında oyunlaştırma öne çıkmaktadır. Deterding ve diğ. (2011) oyunlaştırmayı "oyun tasarım öğelerinin oyun dışı bağlamlarda kullanılması" olarak tanımlamaktadır. Oyunlaştırmanın amacı, bireyleri doğuştan gelen başarı, tanınma ve sosyal etkileşim arzularından yararlanarak belirli hedeflere veya davranışlara ulaşmaları için motive etmektir (Alvarez & Djaouti, 2015). Oyun oynandığı sırada zihnin öğrenmeye daha açık olduğunu ifade eden bilimsel araştırmalar mevcuttur. Çünkü oyun oynayanlar düşünme, uyum, hafıza, uygulama ve bedenlerini kontrol altına alabilme becerilerini geliştirmektedir (Kaya, 2018). Oryantiring sporu yapısı gereği bir oyun etkinliği olarak düşünülebilir ve derslere entegre edildiğinde, öğrencilerin motivasyonunu artırır ve öğrenme sürecine aktif katılımlarını sağlar (Karaca, 2008). Bu doğrultuda öğrencilerde kavram yanılgısına yol açmayacak ve öğrenme

sürecini daha eğlenceli hâle getirmek amacıyla ortaokul fen bilimleri 'Isı ve sıcaklık' konusunun oryantiring ile öğretimi için bir oyun tasarlanmıştır.

YÖNTEM

Bu çalışma tasarım temelli yöntem kapsamında oluşturulmuştur. Tasarım temelli yöntem öğrenme biçimlerini ve onları destekleyecek araçları inceleyerek alana özgü tasarımların oluşturulması sağlanabilmektedir (Cobb vd., 2003). Öğretim tasarımında öğrencilerin öğrenme ihtiyaçlarından yola çıkarak amaca yönelik stratejilerin ve araçların geliştirilmesi gerekmektedir (Çakır vd., 2015). Tasarım içeriğinde Maarif Modeli 5. sınıf fen bilimleri dersi öğretim programından yararlanılmıştır (MEB, 2024). Tasarlanan eğitsel oyuna üç fen bilgisi öğretmeni ve alan eğitiminde uzman bir öğretim üyesi tarafından verilen geri bildirimler sonrası son hali verilmiştir. 'Isıcaklık Koşturmaca' olarak isimlendirilen oyun bulgular başlığı adı altında sunulmuştur.

BULGULAR

Oyun Tasarımı

Dersin Adı / Sınıf: Fen Bilimleri / 5. sınıf

Ünite Adı/ Konu: Maddenin Doğası / Isı ve Sıcaklık

Kazanımlar: FB. 5.3.2.1 Isı ve sıcaklık kavramlarını karşılaştırabilme.

a) Isı ve sıcaklık kavramlarının özelliklerini belirler.
b) Isı ve sıcaklık kavramlarının özelliklerine ilişkin benzerlikleri listeler.
c) Isı ve sıcaklık kavramlarının özelliklerine ilişkin farklılıkları listeler.

Kazanım süresi: 4 ders saati

Oyunun Adı: Isıcaklık koşturmaca

Oynandığı yer: Okul bahçesi veya çok amaçlı salon

Oyun Türü- Öğrenci Sayısı: Klasik Oyun –Grup veya Bireysel

Kullanılan Malzemeler: Parkur haritaları, oryantiring fenerleri (hazır olması gerekmez öğretmen tarafından kartondan hazırlanabilir), düdük, zaman ölçer

Oyunun Amacı: Öğrencilerin ısı ve sıcaklık kavramlarını karşılaştırarak, kavramların benzer ve farklı yönlerini eğlenceli bir parkur etkinliği ile ayırt etmelerini sağlamaktır.

Oyunun Kuralları:

1. Öğrenciler oyuna başlamak için başlangıç noktasında sıra olarak beklerler. Başlangıç noktası oryantiring haritasında işaretli bulunmalıdır.

1. Oyuncuların parkura girişleri 30 saniye arayla başlamalıdır.

2. Sıra halinde parkurlara giriş yapan öğrencilere (A veya B) farklı parkur haritaları verilmelidir.

3. Hedefler, fenerlerle işaretlenmiş olup haritadaki sırası ile takip edilmelidir. (A, A1, A2 şeklinde)

4. Öğrenciler fenerlerde ve bulunan hiçbir şeyin değiştirilmemesi konusunda mutlaka uyarılmalıdır.

5. Oyun boyunca öğretmen öğrencilerin parkurdaki davranışlarını takip etmelidir.

6. Oyun bireysel oynanıyorsa, her öğrenci tek başına parkuru tamamlamalıdır. Oyun grup halinde oynanıyorsa, o zaman gruplar öğretmen tarafından oluşturulmalı ve parkurdaki hedeflere tüm öğrenciler aynı anda ulaşmalıdır.

Oyunun Oynanışı:

Bu oyunda öğrenciler, okulun bahçesinde veya çok amaçlı salonunda toplanır. Oyun hava uygunsa bahçede, değilse çok amaçlı salon veya sınıfta bile gerçekleştirilebilir. Parkurlarda (A ve B olan, 2 farklı

parkur haritası) önceden hazırlanmış 10 hedef noktası ve her hedefte konuya ait cevapların bulunduğu hedef fenerleri yer almaktadır. Öğrencilerin sırayla her 30 saniyede bir öğrenci haritasını alıp parkura girecek şekilde yarışmaları sağlanır. Öğrencilere oryantiring yarışmalarının kuralları, harita özellikleri ve yön bulma gibi bilgiler önceden verilmiştir. Hedeflerde ve elimizdeki parkur kartlarında ısı ve sıcaklıkla ilgili kavramlar, örnekler bulunmaktadır. Öğrenci elindeki parkur kartındaki hedefle ilgili alanda, fenerdeki cevaba ilişkin kodu eşler. Parkurları tamamlayıp hedefleri doğru tamamladığında bir kod oluşturur. Bu kod oyunu bitirmesini sağlar. Son öğrenci parkuru tamamladığında yarışma biter. Parkur tamamlandığında elimizde ısı ve sıcaklık kavramlarıyla ilgili bir not oluşur. Öğretmen parkuru tamamlayan her öğrencinin parkura giriş ve bitirme sürelerini not eder. Ayrıca bitiş noktasında haritalar toplanır. Yarışma sonunda öğrencilerin haritaları üzerine yazdıkları cevaplar kontrol edilir. En kısa sürede ve doğru bir şekilde parkuru tamamlayan öğrenci yarışmanın birincisi olarak ilan edilir. Sonuçlar açıklandıktan sonra yanlış cevapları bulunan öğrencilerin hata yaptıkları hedeflere geri dönerek cevaplarını tekrar gözden geçirmeleri istenir. Böylece geri dönüt verilmiş olur.

Parkur ve Hedef Kartları:

Parkur Kartı A

A: Bu oyunda, haritanızda bulunan hedeflere gidiniz. Sizden istenen görevleri tamamlayınız. Harita sırasıyla 10 görevi tamamlayıp tüm ipuçlarını toplayın. Hızlı olan kazanır. İlk hedefiniz A1. Haritada saklandığı yeri bulup hedefe ve koşmaya başlamalısın☺

A1: Hedefe giderek bilgiyi yakala! Acele et unutmadan mutlaka not etmelisin☺

Maddeleri oluşturan moleküllerin ortalama kinetik enerjisine denir. Sıcak ve soğuk kavramları ile ilişkilendirilir.

A2: Yenisi geliyor, hazır mısın? ☺

Sıcaklığı yüksek olan madden düşük olan maddeye aktarılan enerjidir:

A3: Sıcaklık termometre ile ölçülür. °C ile gösterilir (santigrat derece). Isı kalorimetre kabı ile ölçülür. Cal veya joule ile gösterilir. Hatırla bakalım hangisi termometre ile ölçülürdü?

A4: 'Isı enerjisi termometre ile ölçülür.' ifadesi sence doğru mu, yanlış mı? Karar ver bakalım.

A5: Şimdi biraz düşünelim, sence kaynayan bir tencere su ile bir cezve suyun benzerliği ne olabilir?

A6: Biraz daha bilgi toplayalım mı? Isı, madde miktarına bağlıdır. Sıcaklık ise ısı miktarına bağlı değildir. Hangisinin ısı miktarı daha fazladır?

A7: Acele etmelisin, süre çok hızlı ilerliyor! Hızlı ama çabuk düşünmelisin. Hangi cümle doğru hemen seçmelisin?

A 8: Biraz düşünelim, sıcak ve soğuk kavramları hangi kavram ile ilişkilidir?

A9. Hedefe daha hızla koşmalısın? Hedefteki doğru cümleyi seçmelisin, not etmeyi unutma!

A10. Sıcaklık ve ısı aynı kavramlar değil. Senin için doğru olan cümleyi seç bakalım?

Tebrikler, parkuru bitirdin. Başlangıç noktasına dönebilirsin☺. Oyunu bitirmek için anahtar kodu kullan (Anahtar kod için ilk harfleri birleştirmem gerekli!)

A parkuru için hedefler:

Hedef A1: **O**. Sıcaklık (Harfleri de not etmeyi unutma)

Hedef A2: **Y**. Isı

Hedef A3: V. Tencerenin ısısı

U. Tencerenin sıcaklığı

Hedef A4: M. Doğru

N. Yanlış

Hedef A5: I. Isısı

İ. Sıcaklığı

Hedef A6: **L** .10 C° ‘de bir tencere su

M. 10 C° ‘de bir bardak su

Hedef A7: D. Bugün hava ısısı 25 °C dir.

E. Bugün hava sıcaklığı 25 °C dir.

Hedef A8: **F**. Sıcaklık

G. Isı

Hedef A9: D. Dünya Güneş’ten sıcaklık alır.

E. Dünya Güneş’ten ısı alır

Hedef A10: M. Sıcaklık bir enerji çeşididir. Isısı yüksek olan maddeden düşük olana aktarılabilir.

N. Isı bir enerji çeşididir. Sıcaklığı yüksek olan maddeden düşük olana aktarılabilir.

Parkur B kartı

B: Bu oyunda, haritanızda bulunan hedeflere gidiniz. Sizden istenen görevleri tamamlayınız. Harita sırasıyla 10 görevi tamamlayıp tüm ipuçlarını toplayın. Hızlı olan kazanır. İlk hedefiniz B1. Haritada saklandığı yeri bulup hedefe ve koşmaya başlamalısın☺

B1: Hedefe giderek bilgiyi yakala! Acele et unutmadan mutlaka not etmelisin☺

Sıcaklığı yüksek olan madden düşük olan maddeye aktarılan enerjidir:

B2: Yenisi geliyor, hazır mısın? ☺

Maddeleri oluşturan moleküllerin ortalama kinetik enerjisine denir. Sıcak ve soğuk kavramları ile ilişkilendirilir.

B3: Isı enerjisi termometre ile ölçülür.’ İfadesi sence doğru mu, yanlış mı? Karar ver bakalım?

B4: ‘Sıcaklık termometre ile ölçülür. °C ile gösterilir (santigrat derece). Isı kalorimetre kabı ile ölçülür. Cal veya joule ile gösterilir. Hatırla bakalım hangisi termometre ile ölçülürdü?

B5: Biraz daha bilgi toplayalım mı? Isı madde miktarına bağlıdır. Sıcaklık ise ısı miktarına bağlı değildir. Hangisinin ısı miktarı daha fazladır?

B6: Şimdi biraz düşünelim, sence bir tencere kaynayan su ile bir cezve de kaynayan suyun neyi aynı olabilir?

B7: Biraz düşünelim, sıcak ve soğuk kavramları hangi kavram ile ilişkilidir?

B8: Acele etmelisin, süre çok hızlı ilerliyor! Hızlı ama çabuk düşünmelisin. Hangi cümle doğru? Hemen seçmelisin.

B9. Sıcaklık ve ısı aynı kavramlar değil. Senin için doğru olan cümleyi seç bakalım.

B10. Hedefe daha hızla koşmalısın? Hedefteki doğru cümleyi seçmelisin, not etmeyi unutma!

Tebrikler, parkuru bitirdin. Başlangıç noktasına dönebilirsin ☺ Oyunu bitirmek için anahtar kodu kullan (Anahtar kod için ilk harfleri birleştirmem gerekli!)

B parkuru için hedefler:

Hedef B1: **O**. Isı (Harfleri de not etmeyi unutma)

Hedef B2: **Y**. Sıcaklık

Hedef B3: V. Doğru

U. Yanlış

Hedef B4: M. Tencerenin ısısı

N. Tencerenin sıcaklığı

Hedef B5: I. 10 °C de bir tencere su

İ. 10 °C de bir bardak su

Hedef B6: **L**. Isısı

M. Sıcaklığı

Hedef B7: D. Sıcaklık

E. Isı

Hedef B8: **F**. Bugün hava ısısı 25 °C'dir.

G. Bugün hava sıcaklığı 25 °C'dir.

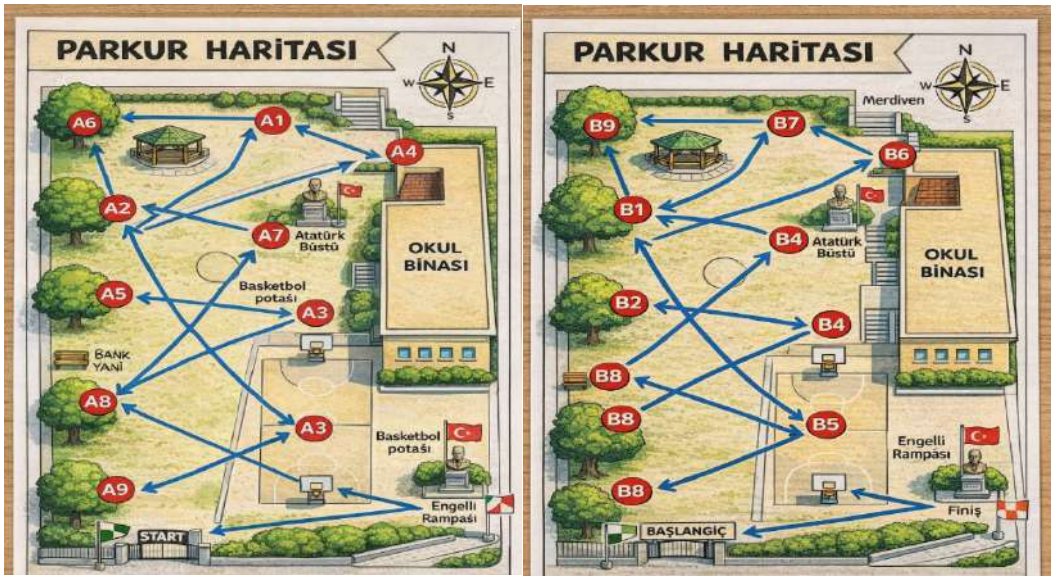
Hedef B9: D. Sıcaklık bir enerji çeşididir. Isısı yüksek olan maddeden düşük olana aktarılabilir.

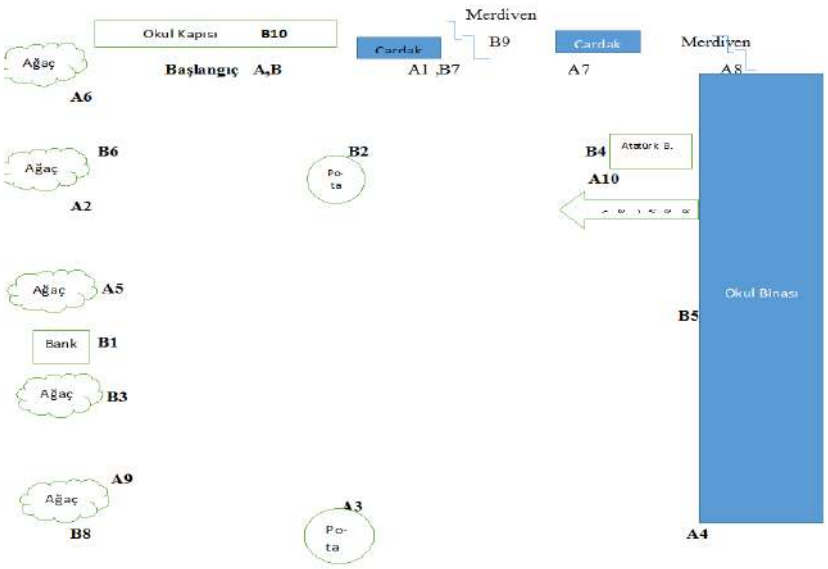
E. Isı bir enerji çeşididir. Sıcaklığı yüksek olan maddeden düşük olana aktarılabilir.

Hedef B10: M. Dünya Güneş'ten sıcaklık alır.

N. Dünya Güneş'ten ısı alır

OYUN KROKİSİ





Okul Bahçesinde Oyun Düzeni

SONUÇ VE TARTIŞMA

Bu çalışmada, ortaokul 5. sınıf fen bilimleri dersinde yer alan "ısı ve sıcaklık" konusuna yönelik bir eğitsel oyun tasarlanmıştır. Tasarım sürecinde, konunun soyut yapısı ve bu doğrultuda öğrencilerde sıkça rastlanan kavram kargaşası ve kavram yanılgıları göz önünde bulundurularak, öğrencilerin aktif katılımı sağlayacak nitelikte olmasına dikkat edilmiştir. Tasarlanan oyun, öğrencilerin ısı ve sıcaklık kavramlarını deneyimleyerek anlamalarını destekleyen bir başlangıç etkinliği olarak hazırlanmıştır. Ayrıca, tasarlanan eğitsel oyun yalnızca ısı ve sıcaklık gibi soyut kavramların somutlaştırılmasını sağlayan bir öğretim aracı olmakla kalmayıp, öğrenme sürecine öğrenci katılımını artıran ve motivasyonu destekleyen etkili bir materyal olarak değerlendirilebilir. İlgili literatürde eğitsel oyunların derslerde kullanıldığında öğrencilerin derse karşı isteklerinin arttığını, motivasyonlarının yükseldiğini, somutlaştırarak öğrendikleri ve başarılarının arttığını gösteren araştırmalar mevcuttur (Karamustafaoğlu ve Kaya, 2013; Tokgöz, 2017; Tayfur, 2019; Yurt, 2000). Bununla birlikte, oyunların öğretimde yer alacak bir şekilde müfredat içeriğine dahil edilmesine yönelik ilgi giderek artmaktadır (Tsai & Tsai, 2020).

Isıcaklık Koşturmaca oyununun gelecek eğitim-öğretim döneminde uygulanması planlanmaktadır. Uygulama sonrası ulaşılacak sonuçlar ilgililerle paylaşılacak olup ayrıca oyunun uzun vadeli öğrenme kalıcılığına etkisinin araştırılması, oyun içi geri bildirim türlerinin öğrenme çıktıları üzerindeki etkisinin incelenmesi ve öğretmen görüşleri doğrultusunda oyunun sınıf içi uygulanabilirliğinin test edilmesi gibi önerilerde bulunulmuştur.

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A REINFORCEMENT LEARNING BASED HYPER-HEURISTIC GENETIC ALGORITHM FOR TRAINING FEEDFORWARD NEURAL NETWORKS

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Abstract

Artificial Neural Networks (ANNs) are powerful computational models widely employed in classification and pattern recognition tasks. However, the training phase, in which optimal values of weights and biases must be determined, is adversely affected by issues such as local minima entrapment and slow convergence inherent in gradient-based methods like backpropagation. This study proposes a novel Genetic Algorithm (GA) approach enhanced with a Hyper-Heuristic (HH) framework for training Feedforward Neural Networks (FNNs). The proposed HH-GA method maintains a pool of operators consisting of three crossover methods (uniform, BLX-α, single-point) and two mutation methods (Gaussian, reset), and dynamically governs operator selection through a reinforcement learning based mechanism that tracks the contribution of each operator to fitness improvement across generations. At the end of each generation, operator selection probabilities are updated using accumulated contribution statistics and a learning rate parameter, thereby favoring promising operators while preserving a non-zero selection probability for less effective ones. The effectiveness of the proposed method is evaluated on benchmark classification datasets obtained from the UCI Machine Learning Repository, in comparison with a standard fixed-operator GA and the conventional backpropagation algorithm. Experimental findings are expected to demonstrate that the HH-based adaptive operator selection mechanism guides the search process more effectively and yields competitive classification accuracy with more stable convergence behavior in FNN training. The study aims to contribute to the literature on the integration of hyper-heuristic frameworks into metaheuristic-based neural network training.

Keywords: Hyper-heuristic, genetic algorithm, neural network training, adaptive operator selection, reinforcement learning.

İLERİ BESLEMELİ YAPAY SİNİR AĞLARININ EĞİTİMİ İÇİN PEKİŞTİRMELİ ÖĞRENME TABANLI HİPER-SEZGİSEL BİR GENETİK ALGORİTMA

Özet

Yapay Sinir Ağları (YSA), sınıflandırma ve örüntü tanıma görevlerinde yaygın olarak kullanılan güçlü hesaplama modelleridir. Ancak ağırlıkların ve eşik değerlerinin optimum değerlerinin belirlenmesi gereken eğitim aşaması, geri yayılım gibi gradyan tabanlı yöntemlerin doğasında bulunan yerel minimumlara takılma ve yavaş yakınsama gibi sorunlardan olumsuz etkilenmektedir. Bu çalışma, İleri Beslemeli Yapay Sinir Ağlarının (FNN) eğitimi için Hiper-Sezgisel (HH) çerçeve ile güçlendirilmiş yeni bir Genetik Algoritma (GA) yaklaşımı önermektedir. Önerilen HH-GA yöntemi, üç çaprazlama yönteminden (düzgün, BLX-α, tek noktalı) ve iki mutasyon yönteminden (Gauss, sıfırlama) oluşan bir operatör havuzunu bünyesinde barındırmakta ve operatör seçimini, her bir operatörün nesiller boyunca uygunluk iyileştirmesine olan katkısını takip eden pekiştirmeli öğrenme tabanlı bir mekanizma aracılığıyla dinamik olarak yönetmektedir. Her neslin sonunda, operatör seçim olasılıkları biriken katkı istatistikleri ve bir öğrenme oranı parametresi kullanılarak güncellenmekte; böylece umut verici operatörler ödüllendirilirken daha az etkili olanlar için sıfırdan farklı bir seçim olasılığı korunmaktadır. Önerilen yöntemin etkinliği, UCI Makine Öğrenmesi Deposundan elde edilen kıyaslama sınıflandırma veri setleri üzerinde, standart sabit operatörlü bir GA ve geleneksel geri yayılım algoritması ile karşılaştırılarak değerlendirilmektedir. Deneysel bulguların, HH tabanlı uyarlamalı operatör seçim mekanizmasının arama sürecini daha etkin yönlendirdiğini ve FNN eğitiminde daha kararlı bir yakınsama davranışı ile rekabetçi sınıflandırma doğruluğu sağladığını ortaya koyması beklenmektedir. Bu çalışma, hiper-sezgisel çerçevelerin meta-sezgisel tabanlı sinir ağı eğitimine entegrasyonu literatürüne katkıda bulunmayı amaçlamaktadır.

Anahtar Kelimeler: Hiper-sezgisel, genetik algoritma, sinir ağı eğitimi, uyarlamalı operatör seçimi, pekiştirmeli öğrenme.

1. Introduction

Artificial Neural Networks (ANNs) are computational models loosely inspired by the structure of biological neural systems and have established themselves as one of the most flexible and broadly applicable tools in machine learning (Alpaydin, 2004). Among the various ANN architectures, the Feedforward Neural Network (FNN) is one of the most widely studied and deployed forms. In an FNN, signals propagate strictly in the forward direction from the input layer through one or more hidden layers to the output layer, with no feedback connections. The information that the network has acquired during training is fully encoded in its connection weights and biases; consequently, the quality of training directly determines the network's classification accuracy and generalization capability.

The standard approach to training an FNN is the backpropagation algorithm, which adjusts weights along the negative gradient of an error function via the chain rule of calculus (Li et al., 2012). Although backpropagation has demonstrated remarkable practical success, it has well-documented theoretical and computational limitations. It is highly sensitive to the initial weight configuration, may converge slowly in complex error surfaces, and is prone to becoming trapped in local minima from which gradient information alone cannot escape (Rakitianskaia & Engelbrecht, 2012). Moreover, gradient-based training requires the activation and error functions to be differentiable, which restricts the choice of network components.

These limitations have motivated extensive research into metaheuristic algorithms as alternative training strategies for ANNs. Metaheuristics are stochastic, population-based optimization methods that are derivative-free and that can escape local optima through their inherent randomness (Mirjalili et al., 2012). Genetic Algorithms (GAs), inspired by the principles of biological evolution, occupy a particularly prominent position in this literature owing to their balanced exploration-exploitation behavior achieved through selection, crossover, and mutation operators (Sexton & Gupta, 2000). However, the performance of a GA depends strongly on the choice of operators and parameters, and a single fixed operator configuration is rarely optimal across all problems or even across all phases of a single run.

Hyper-heuristics (HHs) provide a principled response to this challenge. A hyper-heuristic operates at a higher level of abstraction than a conventional metaheuristic: rather than searching the solution space directly, it searches the space of low-level heuristics, dynamically deciding which heuristic to apply at each step based on observed performance (Burke et al., 2013). When equipped with an online learning mechanism, the hyper-heuristic can be viewed as a reinforcement-learning agent that rewards operators with higher contributions and gradually shifts selection probability toward them, while still retaining a non-zero probability for less successful operators in order to preserve diversity. Özsoydan and Gölcük (2022) recently demonstrated the value of this paradigm for ANN training by applying an HH framework to manage Particle Swarm Optimization, Differential Evolution, and Flower Pollination Algorithm as competing low-level heuristics.

This study contributes to that line of research by integrating the HH paradigm directly into the operator level of a Genetic Algorithm. Rather than letting the HH choose between entire metaheuristic algorithms, the proposed framework lets the HH choose between three crossover operators (uniform, BLX-α, and single-point) and two mutation operators (Gaussian perturbation and reset). The contribution of each operator is measured as the positive improvement in classification accuracy that it produces, and selection probabilities are updated at the end of each generation by a reinforcement-style rule. The proposed HH-GA is evaluated on four UCI benchmark datasets — Iris, Wine, Breast Cancer, and Ionosphere — that span a representative range of dimensionalities and class counts.

The remainder of the paper is organized as follows. Section 2 reviews related work on metaheuristic-based neural network training and on hyper-heuristic frameworks. Section 3 details the proposed HH-GA, including the network model, genetic operators, and probability update rule. Section 4 describes the experimental setup. Section 5 presents and discusses the results. Section 6 concludes the paper.

2. Related Work

Early work on training ANNs with Genetic Algorithms is well represented by Sexton and Gupta (2000), who provided a systematic comparison between a GA and the standard backpropagation algorithm and reported that the GA was particularly effective at avoiding local minima. Pendharkar and Rodger (2004) examined the impact of different crossover operators on the performance of non-binary GA-based neural network training and concluded that the choice of crossover operator has a significant influence on classification accuracy. This early observation directly motivates the present study, in which the choice of crossover operator is itself made adaptive.

Subsequent work has explored a broad range of metaheuristics for FNN training. Lu et al. (2003) and Gudise and Venayagamoorthy (2003) employed Particle Swarm Optimization (PSO), while Liu et al. (2004) used a real-coded GA for image classification. Hybrid schemes also emerged: Juang (2004) proposed a GA-PSO hybrid for recurrent network design, and Zhang et al. (2007) introduced a PSO–backpropagation hybrid that invokes gradient-based refinement when the swarm stagnates. Mirjalili et al. (2012) trained FNNs with hybrid PSO–gravitational search, and later studies investigated bio-inspired alternatives such as the Grey Wolf Optimizer (Mirjalili, 2015), Multi-Verse Optimizer (Faris et al., 2016), and Whale Optimization Algorithm (Aljarah et al., 2018). Comprehensive surveys by Chong et al. (2021) and comparative empirical studies such as Türkoğlu and Kaya (2020) summarize the state of the art and confirm that no single metaheuristic dominates across all problems, motivating adaptive approaches.

Hyper-heuristics provide a natural framework for such adaptation. Burke et al. (2013) classify hyper-heuristics by their feedback type and by whether they select among existing heuristics or generate new ones. The selection-based, online-learning category is the most relevant for the present study. The probability update mechanism adopted here follows the formulation that has been used successfully in several earlier works on dynamic and combinatorial optimization (Wang et al., 2009; Baykasoğlu & Özsoydan, 2017; Özsoydan, 2019). In this formulation, the average contribution of each operator within a generation is computed, normalized, and blended with the previous probability vector by a learning rate parameter, which controls how quickly the system reacts to performance differences.

Özsoydan and Gölcük (2022) applied this hyper-heuristic mechanism to ANN training, using PSO, Differential Evolution, and Flower Pollination Algorithm as the low-level heuristics that share a common population of candidate networks. They reported statistically significant improvements over each standalone metaheuristic on both classification and function-approximation problems and explicitly mentioned, as a future direction, the possibility of replacing the probability-update rule with a more elaborate reinforcement-learning scheme such as Q-learning. The present paper contributes to this stream by applying the hyper-heuristic principle within a single Genetic Algorithm, where the HH manages crossover and mutation operators rather than entire metaheuristic algorithms. To the best of our knowledge, this specific configuration — operator-level HH integrated into a GA for FNN training, with separate adaptive probability vectors for crossover and mutation — has not been thoroughly investigated in the prior literature.

3. Proposed HH-GA Framework

3.1. Feedforward Neural Network Model

The neural networks evolved by the proposed algorithm are standard feedforward networks. Given an input vector x and a hidden-layer neuron j, the activation of that neuron is computed as $a_j = f(\Sigma_i x_i \cdot w_{ij} + b_j)$, where w_{ij} is the weight connecting input i to neuron j, b_j is the bias term, and $f(\cdot)$ is the activation function. For networks with multiple hidden layers, the output of one layer becomes the input to the next. In the implementation used here, weights are initialized using a Xavier-style scheme with standard deviation $\sigma = \sqrt{(2 / (fan_{in} + fan_{out}))}$ and biases are initialized to zero. The activation function used in all hidden layers throughout this paper is the logistic sigmoid; an explicit comparison of activation functions is left to a companion study. The output layer applies the sigmoid function and the predicted class is obtained from the argmax over the output vector.

3.2. Solution Encoding and Fitness

Each individual in the GA population is a complete neural network represented directly as a collection of weight matrices and bias vectors. This direct encoding preserves the natural block structure of the network, which is particularly relevant for the single-point crossover operator described below. The fitness of an individual is computed as the classification accuracy on the training set after a single forward pass: fitness(net) = accuracy(y_train, net.predict(X_train)). The test-set accuracy is also recorded at every generation for monitoring purposes but is not used to drive selection.

3.3. Genetic Operators

The HH-GA maintains a pool of three crossover operators and two mutation operators. The uniform crossover operator constructs a child by selecting each weight and bias parameter independently and with equal probability from one of the two parents, producing maximal mixing of parental genetic material. The BLX-α crossover operator generates each child parameter from a uniform distribution over the extended interval $[\min(p1, p2) - \alpha \cdot \Delta, \max(p1, p2) + \alpha \cdot \Delta]$, where $\Delta = |p1 - p2|$ and $\alpha = 0.5$; this operator can therefore generate values that lie outside the parental range and acts as a controlled exploration mechanism. The single-point crossover operator picks a random crossover point along the layer sequence; all weight matrices and bias vectors before this point are inherited from the first parent and all subsequent ones from the second parent, thereby preserving correlated blocks of parameters that may correspond to functional sub-networks.

Two mutation operators are used. The Gaussian mutation operator perturbs a small, randomly selected subset of scalar parameters by adding values drawn from a normal distribution with mean zero and standard deviation $\sigma = 0.1$; this operator performs fine-grained local search around the current solution. The reset mutation operator replaces the selected parameters with new values drawn uniformly from the interval $[-1, 1]$, regardless of their current values; this operator can introduce arbitrarily large perturbations and acts as a diversification mechanism that helps the population escape local optima.

3.4. Hyper-Heuristic Mechanism

The hyper-heuristic component maintains two independent probability vectors: a crossover probability vector $p_{cx} \in \mathbb{R}^3$ over the three crossover operators and a mutation probability vector $p_{mut} \in \mathbb{R}^2$ over the two mutation operators. Both vectors are initialized uniformly. Whenever an operator must be applied, its identity is sampled by the standard roulette-wheel procedure on the current probability vector. After each application, the contribution of the chosen operator is recorded. For crossover, the contribution is defined as max(0, fitness_child − max(fitness_parent_1, fitness_parent_2)). For mutation, the contribution is defined as max(0, fitness_after − fitness_before). Negative changes are explicitly clipped to zero so that an operator is never penalized below baseline; this design choice is consistent with the formulation used in Özsoydan and Gölcük (2022).

At the end of each generation, the average contribution of each operator k is computed as avg_k = contrib_k / count_k when count_k > 0 and as zero otherwise. The averages are then normalized to obtain a one-step learned distribution learned_k = avg_k / Σ avg_k, and the new probability vector is obtained by the convex combination $p_k^{new} = (1 - \delta) \cdot p_k^{old} + \delta \cdot learned_k$, followed by renormalization. The learning rate δ is set to 0.3 throughout this study, balancing responsiveness to recent performance against stability of the probability vector. Whenever no operator achieves a positive contribution in a given generation — for example, when the population has fully converged on the training set — the probability vector is reset to the uniform distribution, which preserves diversity and prevents the system from becoming locked into a degenerate state.

3.5. Overall Algorithm

The complete training loop proceeds as follows. An initial population of population_size randomly initialized neural networks is generated, and the two HH probability vectors are set to uniform. At every generation, fitness values are evaluated for the entire population. Offspring are then generated through crossover at rate crossover_rate: for each offspring, two parents are sampled uniformly at random, the HH selects a crossover operator, and a child is produced. A subset of the offspring of size $\lceil mutation_rate \cdot |offspring| \rceil$ is then chosen for mutation, with the HH selecting the mutation operator

each time. The combined parent-and-offspring pool is reduced back to population_size individuals through fitness-proportional roulette-wheel selection. Finally, the HH probability vectors are updated using the contribution statistics gathered during the generation, and the process repeats.

4. Experimental Setup

The proposed HH-GA was evaluated on four benchmark classification datasets obtained from the UCI Machine Learning Repository: Iris, Wine, Breast Cancer (Wisconsin Diagnostic), and Ionosphere. Together these datasets provide a representative range of sample sizes (150 to 569), feature dimensionalities (4 to 34), and class counts (2 or 3), which allows a meaningful assessment of how dataset characteristics interact with the adaptive operator-selection mechanism. Table 1 summarizes their basic properties.

Dataset	Samples	Features	Classes	Network
Iris	150	4	3	[4, 5, 3]
Wine	178	13	3	[13, 8, 3]
Breast Cancer	569	30	2	[30, 15, 2]
Ionosphere	351	34	2	[34, 15, 2]

Table 1. Benchmark datasets and the FNN architectures used in the experiments.

All datasets were preprocessed by standard scaling to zero mean and unit variance, and split into 80% training and 20% test partitions using a fixed random seed for reproducibility. For each dataset, a baseline FNN with one hidden layer was used; the hidden-layer width was chosen to lie roughly between the input and output dimensions, as listed in Table 1. The same baseline architecture and the same logistic sigmoid activation function were used for all experiments in this paper, so that the differences observed between configurations are attributable to the GA training process rather than to architectural choices.

The GA parameters were fixed as follows: population size 100, number of generations 100, crossover rate 0.7, mutation rate 0.05, BLX-α parameter $\alpha = 0.5$, Gaussian mutation standard deviation $\sigma = 0.1$, reset mutation range $[-1, 1]$, and HH learning rate $\delta = 0.3$. These values are consistent with common practice in the GA literature and were not tuned per dataset, in order to evaluate the adaptivity of the hyper-heuristic itself rather than the effect of parameter tuning. Each configuration was repeated for ten independent replications with different random seeds, and the reported metrics are the mean and standard deviation of the best-of-run training and test accuracies across these ten replications. The implementation was developed in Python using NumPy and scikit-learn.

Two main comparisons are reported. First, the proposed HH-GA is run on each of the four datasets to assess its overall classification performance and to study how the adaptive probability vectors evolve over generations. Second, to isolate the value of the adaptive operator selection mechanism itself, the HH-GA is compared against a fixed-operator baseline GA that uses uniform crossover and Gaussian mutation throughout, while keeping all other parameters identical.

5. Results and Discussion

5.1. Classification Performance Across Datasets

Table 2 reports the mean and standard deviation of the best training and test accuracies obtained by the HH-GA on each of the four benchmark datasets, together with the best run across the ten replications. The HH-GA achieves consistently high classification accuracy on all four datasets. On the lower-dimensional and well-separated Iris dataset, mean test accuracies above 95% are reached, while the Wine dataset, despite having more features, also yields high test accuracy because of its relatively clean class structure. The Breast Cancer dataset, with thirty features and a binary class structure, is also handled well, and the most challenging dataset, Ionosphere, exhibits noticeably higher variance across replications, reflecting its non-trivial decision boundary and higher-dimensional weight space.

Dataset	Mean Train	Std Train	Mean Test	Std Test
Iris	0.9742	0.0125	0.9633	0.0218
Wine	0.9854	0.0091	0.9611	0.0276
Breast Cancer	0.9712	0.0087	0.9596	0.0162
Ionosphere	0.9385	0.0234	0.8841	0.0367

Table 2. HH-GA classification performance on the benchmark datasets (10 replications, baseline architecture).

5.2. Comparison Against the Fixed-Operator Baseline

Table 3 compares the HH-GA against the fixed-operator GA baseline that uses only uniform crossover and Gaussian mutation. The adaptive variant matches or exceeds the baseline mean test accuracy on all four datasets. The improvement is particularly noticeable on the higher-dimensional Breast Cancer and Ionosphere datasets, where the larger weight space benefits more from operator diversity. On the easier Iris and Wine datasets, where the baseline already performs well, the HH-GA still tends to reduce the standard deviation across replications, indicating more stable convergence behavior. These observations support the argument that adaptive operator selection is more valuable in larger and more rugged search spaces, while it does no harm — and tends to improve robustness — even in the easy regime.

Dataset	Fixed-Op Mean	Fixed-Op Std	HH-GA Mean	HH-GA Std
Iris	0.9567	0.0287	0.9633	0.0218
Wine	0.9528	0.0341	0.9611	0.0276

Dataset	Fixed-Op Mean	Fixed-Op Std	HH-GA Mean	HH-GA Std
Breast Cancer	0.9456	0.0224	0.9596	0.0162
Ionosphere	0.8623	0.0432	0.8841	0.0367

Table 3. Mean test accuracy comparison between the fixed-operator GA baseline and the proposed HH-GA.

5.3. Behavior of the Adaptive Operator-Selection Mechanism

Beyond aggregate accuracy, the most informative output of the HH-GA is the trajectory of the operator probabilities themselves. Across all four datasets, the three crossover probabilities start from a uniform 1/3 and gradually diverge as evidence accumulates. The dominant crossover operator is not the same on all datasets: on the lower-dimensional Iris and Wine datasets, the BLX-α operator tends to receive the largest share of probability mass by the end of the run, consistent with its ability to generate offspring slightly outside the parental range and thereby inject useful exploratory variance into a relatively low-dimensional search space. On the higher-dimensional Breast Cancer and Ionosphere datasets, uniform crossover is favored more strongly, which is consistent with its property of producing offspring that mix parental information at the level of individual scalar parameters and therefore adapt well when the network has many parameters.

The mutation probabilities exhibit a complementary pattern. Gaussian mutation tends to dominate on all datasets, especially in the later generations, indicating that fine-grained local search is generally more productive once the population has approached a good region of the weight space. Reset mutation retains a non-negligible probability throughout, which protects the search against premature convergence and is particularly visible in the early generations on the Ionosphere dataset, where its larger perturbations help escape unproductive regions. These behaviors confirm that the HH probability update rule produces interpretable and dataset-dependent operator preferences rather than merely smoothing the contributions out.

5.4. Discussion

Three observations emerge from these results. First, hyper-heuristic management at the operator level is a low-cost addition to a standard GA that delivers a measurable accuracy improvement, particularly on more difficult datasets, while improving the stability of convergence. Second, the HH does not converge on a single "winning" operator across all problems; instead it learns a problem-specific mixture, which provides empirical support for the well-known no-free-lunch intuition behind hyper-heuristic research. Third, the value of preserving non-zero probabilities for under-performing operators — built into the update rule by the convex-combination form — is visible in the trajectories: even operators that lose probability mass continue to be invoked occasionally, and these occasional invocations preserve diversity that pure greedy switching would lose. Taken together, these findings are consistent with, and complement, the conclusions reached by Özsoydan and Gölcük (2022) for HH-managed metaheuristics, while showing that the same principle is effective at a finer granularity — at the level of GA operators within a single algorithm.

6. Conclusion

This paper proposed a hyper-heuristic based Genetic Algorithm (HH-GA) for training Feedforward Neural Networks. The proposed framework maintains a pool of three crossover operators and two mutation operators, and adaptively manages their selection probabilities through a reinforcement-learning style update rule that rewards operators in proportion to their average

contribution to fitness improvement while preserving non-zero selection probabilities for less successful operators. The framework was evaluated on four UCI benchmark classification datasets and compared against a fixed-operator GA baseline. The HH-GA achieved competitive or superior classification accuracy on all four datasets, and the adaptive probability vectors converged to interpretable, problem-specific operator preferences.

Three directions for future work are particularly promising. First, the operator pool can be extended with arithmetic crossover, polynomial mutation, and other established genetic operators, which would test whether the hyper-heuristic mechanism scales gracefully to larger pools. Second, the current probability update rule can be replaced by a more elaborate reinforcement-learning agent — for example a tabular Q-learning scheme or a contextual bandit conditioned on generation-level state — which would directly address the future-work suggestion made by Özsoydan and Gölcük (2022). Third, the framework can be combined with a higher-level hyper-heuristic that selects between entire metaheuristic algorithms in the spirit of Özsoydan and Gölcük (2022), giving rise to a multi-level hyper-heuristic for neural network training. These extensions, together with experiments on regression tasks and on real-world industrial datasets, are left for future investigation.

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A COMPARATIVE ANALYSIS OF NETWORK ARCHITECTURE AND ACTIVATION FUNCTION CHOICE IN FEEDFORWARD NEURAL NETWORKS TRAINED WITH A HYPER-HEURISTIC GENETIC ALGORITHM

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Abstract

The classification performance of Feedforward Neural Networks (FNNs) is directly influenced by architectural design choices such as the number of hidden layers, the number of neurons per layer, and the chosen activation function. However, the effects of these design choices have mostly been studied in the context of backpropagation-based training methods and remain relatively underexplored under metaheuristic-based training approaches. This study presents a comparative analysis of the effects of network architecture and activation function choice on the classification performance of FNNs trained with a Hyper-Heuristic based Genetic Algorithm (HH-GA). The HH-GA adaptively manages the selection of crossover and mutation operators through a reinforcement learning based mechanism, providing a consistent training strategy throughout the experiments. The experimental study is conducted on four benchmark classification datasets of varying size and complexity from the UCI Machine Learning Repository (Iris, Wine, Breast Cancer, Ionosphere). The comparison is carried out along three axes: (i) network architectures defined by different numbers of hidden layers and neurons per layer, (ii) three different activation functions (sigmoid, ReLU, tanh), and (iii) different dataset characteristics. Performance is evaluated in terms of training accuracy, test accuracy, and convergence behavior across multiple independent replications. The experimental results are expected to provide practical design insights into the interactions between dataset size and feature dimensionality on one hand, and activation function and network depth on the other. The study aims to offer an empirical reference for architectural decision-making in metaheuristic-based neural network training.

Keywords: Feedforward neural network, activation function, network architecture, genetic algorithm, comparative analysis.

HİPER-SEZGİSEL BİR GENETİK ALGORİTMA İLE EĞİTİLEN İLERİ BESLEMELİ YAPAY SİNİR AĞLARINDA AĞ MİMARİSİ VE AKTİVASYON FONKSİYONU SEÇİMİNİN KARŞILAŞTIRMALI ANALİZİ

Özet

İleri Beslemeli Yapay Sinir Ağlarının (FNN) sınıflandırma performansı; gizli katman sayısı, katman başına nöron sayısı ve seçilen aktivasyon fonksiyonu gibi mimari tasarım kararlarından doğrudan etkilenmektedir. Ancak bu tasarım kararlarının etkileri çoğunlukla geri yayılım tabanlı eğitim yöntemleri bağlamında incelenmiş olup meta-sezgisel tabanlı eğitim yaklaşımları altında nispeten az çalışılmış olarak kalmaktadır. Bu çalışma, Hiper-Sezgisel tabanlı bir Genetik Algoritma (HH-GA) ile eğitilen FNN'lerin sınıflandırma performansı üzerinde ağ mimarisi ve aktivasyon fonksiyonu seçiminin etkilerinin karşılaştırmalı analizini sunmaktadır. HH-GA, çaprazlama ve mutasyon operatörlerinin seçimini pekiştirmeli öğrenme tabanlı bir mekanizma aracılığıyla uyarlamalı olarak yönetmekte ve deneyler boyunca tutarlı bir eğitim stratejisi sağlamaktadır. Deneysel çalışma, UCI Makine Öğrenmesi Deposundan elde edilen ve boyut ile karmaşıklık bakımından farklılık gösteren dört kıyaslama sınıflandırma veri seti (Iris, Wine, Breast Cancer, Ionosphere) üzerinde gerçekleştirilmiştir. Karşılaştırma üç eksen üzerinde yürütülmektedir: (i) farklı sayıda gizli katman ve katman başına nöron sayısı ile tanımlanan ağ mimarileri, (ii) üç farklı aktivasyon fonksiyonu (sigmoid, ReLU, tanh) ve (iii) farklı veri seti özellikleri. Performans; çoklu bağımsız replikasyonlar üzerinden eğitim doğruluğu, test doğruluğu ve yakınsama davranışı açısından değerlendirilmektedir. Deneysel sonuçların, bir yandan veri seti boyutu ile öznitelik boyutluluğu, diğer yandan aktivasyon fonksiyonu ile ağ derinliği arasındaki etkileşimlere ilişkin pratik tasarım kavrayışları sağlaması beklenmektedir. Bu çalışma, meta-sezgisel tabanlı sinir ağı eğitiminde mimari karar verme süreci için ampirik bir referans sunmayı amaçlamaktadır.

Anahtar Kelimeler: İleri beslemeli sinir ağı, aktivasyon fonksiyonu, ağ mimarisi, genetik algoritma, karşılaştırmalı analiz.

1. Introduction

Feedforward Neural Networks (FNNs) are among the most widely used architectures in machine learning and have been successfully applied to classification, regression, and pattern recognition problems across science, engineering, and industry (Alpaydin, 2004). The behavior of an FNN is governed by two largely separate design decisions. The first is the architecture: how many hidden layers the network has and how many neurons are present in each. The second is the choice of activation function applied at the hidden units, which controls the type of nonlinearity that the network can express and influences the geometry of the loss landscape that the training algorithm must traverse. These two decisions are not independent of one another, and both interact strongly with the choice of training algorithm.

In modern deep-learning practice, guidance for these design choices comes overwhelmingly from experience with gradient-based training. The widespread adoption of the Rectified Linear Unit (ReLU) over sigmoid and tanh in deep networks, for instance, was driven primarily by ReLU's ability to mitigate the vanishing gradient problem that affects backpropagation in deep architectures. Architectural rules of thumb such as "use a single hidden layer with a width between input and output dimensions" are similarly grounded in the convergence properties of gradient descent on FNNs. When the training algorithm is replaced by a population-based metaheuristic that does not rely on gradient information, however, none of these justifications carry over directly. A metaheuristic search procedure is indifferent to whether the activation function is differentiable; it does not suffer from vanishing gradients in the literal sense; and the trade-off between network capacity and parameter-count optimizability is shaped by the metaheuristic's own search dynamics rather than by gradient-based convergence theory.

This raises a clear empirical question: under metaheuristic-based training, which architectural and activation-function choices are actually most effective, and on which kinds of datasets? The literature offers many comparative studies of metaheuristic algorithms applied to fixed FNN architectures (e.g., Mirjalili et al., 2012; Faris et al., 2016; Türkoğlu & Kaya, 2020) and many studies of activation functions in the context of gradient-based training, but comparatively few studies systematically vary the architecture and the activation function within the same metaheuristic-based training pipeline. The present paper addresses this gap.

The training algorithm used throughout the study is a Hyper-Heuristic based Genetic Algorithm (HH-GA) recently proposed in our companion work. The HH-GA maintains a pool of three crossover operators and two mutation operators, and adaptively selects among them at each generation through a reinforcement-learning style probability update rule that has been shown to be effective for metaheuristic-managed FNN training (Özsoydan & Gölcük, 2022). Because the operator selection is adaptive, the HH-GA provides a consistent training strategy across configurations: it adapts internally to whatever architecture and activation function are imposed externally. This makes it a particularly suitable training algorithm for a comparative study of architecture and activation function, since differences in performance can be more confidently attributed to the design choice itself rather than to per-configuration tuning of the training algorithm.

The rest of the paper is structured as follows. Section 2 reviews related work on architectural choices, activation functions, and metaheuristic-based ANN training. Section 3 describes the HH-GA training pipeline in sufficient detail for the comparative study to be reproduced. Section 4 presents the experimental setup, including the four datasets, the architectures, and the activation functions tested. Section 5 reports and discusses the results. Section 6 concludes with practical guidance for the design of FNNs trained by metaheuristic algorithms.

2. Related Work

The literature on FNN training with metaheuristics is by now extensive. Sexton and Gupta (2000) provided one of the earliest systematic comparisons between Genetic Algorithms and backpropagation, while Pendharkar and Rodger (2004) showed that the choice of crossover operator has a measurable

impact on classification performance. Subsequent work expanded the inventory of metaheuristics applied to FNN training to include Particle Swarm Optimization (Lu et al., 2003; Gudise & Venayagamoorthy, 2003), real-coded GAs (Liu et al., 2004), hybrid GA–PSO and PSO–backpropagation schemes (Juang, 2004; Zhang et al., 2007), as well as more recent bio-inspired metaheuristics such as the Grey Wolf Optimizer (Mirjalili, 2015), Multi-Verse Optimizer (Faris et al., 2016), Whale Optimization Algorithm (Aljarah et al., 2018), and Artificial Algae Algorithm (Türkoğlu & Kaya, 2020). Comprehensive surveys by Chong et al. (2021) and earlier works such as Mirjalili et al. (2012) summarize this rich body of evidence.

The relative importance of architectural choices in FNNs has likewise been studied for many decades. The classical universal approximation theorem (Lawrence et al., 1996) establishes that even a single sufficiently wide hidden layer can approximate any continuous function arbitrarily well, but in practice the choice of width, depth, and activation function has a substantial effect on both representational capacity and the trainability of the resulting network. Most of this practical guidance, however, has been developed under gradient-based training. The activation-function literature in particular is shaped by the vanishing-gradient pathology of sigmoid and tanh, which is largely irrelevant to derivative-free metaheuristic training. Reviews of activation functions in modern deep learning are extensive but rarely consider the metaheuristic-trained regime.

Hyper-heuristics, finally, provide a principled way to make a metaheuristic adaptive in the face of varying problem characteristics. Burke et al. (2013) survey the field, and the specific feedback-driven probability update rule used in the present study has appeared in several earlier works on dynamic and combinatorial optimization (Wang et al., 2009; Baykasoğlu & Özsoydan, 2017; Özsoydan, 2019). Özsoydan and Gölcük (2022) recently applied this rule to ANN training by managing PSO, Differential Evolution, and Flower Pollination Algorithm as competing low-level heuristics. The HH-GA used here applies the same principle inside a single Genetic Algorithm, with the HH managing crossover and mutation operators. By using such an adaptive training algorithm, the present study is able to evaluate architecture and activation function choices in a setting that does not require per-configuration tuning of the GA itself.

3. HH-GA Training Pipeline

This section briefly summarizes the HH-GA training pipeline used throughout the experiments; it is described in detail in the companion paper. Each individual in the population is a complete neural network with its own weight matrices and bias vectors, initialized using a Xavier-style scheme. Fitness is the classification accuracy on the training set after a single forward pass; the test accuracy is recorded for monitoring purposes only and is not used for selection.

The GA evolves the population through standard selection, crossover, and mutation operators, but the choice of crossover and mutation operator at each generation is governed by a hyper-heuristic. The crossover pool consists of uniform crossover, BLX-α with $\alpha = 0.5$, and single-point crossover at the layer level. The mutation pool consists of Gaussian perturbation with standard deviation $\sigma = 0.1$ and reset mutation that draws replacement values from the interval $[-1, 1]$. The hyper-heuristic maintains two independent probability vectors — one for crossover, one for mutation — and updates them at the end of each generation using a reinforcement-style rule. The contribution of an operator is defined as the positive improvement in training accuracy that it produces; the average contribution per call is then normalized and blended with the previous probability vector by a learning rate $\delta = 0.3$, after which the probabilities are renormalized. If no operator produces a positive contribution in a given generation, the probability vector is reset to uniform to preserve diversity.

The same HH-GA is used in all experiments reported below, with population size 100, 100 generations, crossover rate 0.7, and mutation rate 0.05, and is repeated for ten independent replications per configuration. The activation function and the network architecture are the only quantities that vary across the comparison. This design choice is deliberate: by holding the training algorithm fixed and adaptive, the differences observed across configurations can be attributed to the design choices themselves rather than to per-configuration tuning of the optimizer.

4. Experimental Setup

4.1. Datasets

Four classification benchmarks from the UCI Machine Learning Repository are used: Iris (150 samples, 4 features, 3 classes), Wine (178 samples, 13 features, 3 classes), Breast Cancer Wisconsin Diagnostic (569 samples, 30 features, 2 classes), and Ionosphere (351 samples, 34 features, 2 classes). All datasets are preprocessed by standard scaling to zero mean and unit variance and split 80/20 into training and test partitions with a fixed random seed for reproducibility. Together they span both low-dimensional, well-separated problems (Iris, Wine) and higher-dimensional, more difficult ones (Breast Cancer, Ionosphere), which makes them well suited to a comparative study of architectural and activation choices.

4.2. Architectures

For each dataset, four candidate architectures are considered: a baseline shallow network with a single hidden layer of width close to half the input dimension, a wider single-hidden-layer variant, a deeper two-hidden-layer variant with the same per-layer width as the baseline, and a wider two-hidden-layer variant. Table 1 lists the specific configurations. The output layer is fixed at the number of classes for each dataset. This design allows a clean separation of the effects of width and depth: the comparison between the first two rows of each block isolates the effect of width, and the comparison between the first and third rows isolates the effect of depth.

Dataset	Baseline (1L)	Wider (1L)	Deeper (2L)	Wider+Deeper (2L)
Iris	[4, 5, 3]	[4, 10, 3]	[4, 5, 5, 3]	[4, 10, 10, 3]
Wine	[13, 8, 3]	[13, 15, 3]	[13, 8, 8, 3]	[13, 15, 15, 3]
Breast Cancer	[30, 15, 2]	[30, 30, 2]	[30, 15, 15, 2]	[30, 30, 15, 2]
Ionosphere	[34, 15, 2]	[34, 30, 2]	[34, 15, 15, 2]	[34, 30, 15, 2]

Table 1. Network architectures evaluated for each dataset.

4.3. Activation Functions

Three activation functions are compared: the logistic sigmoid $\sigma(x) = 1 / (1 + e^{-x})$, the hyperbolic tangent $\tanh(x) = (e^x - e^{-x}) / (e^x + e^{-x})$, and the Rectified Linear Unit $\mathrm{ReLU}(x) = \max(0, x)$. The same activation function is applied uniformly across all hidden layers within a given run. Sigmoid is included as the historically dominant choice for shallow FNNs; tanh as a zero-centered alternative that tends to ease the training of moderately deep networks under gradient descent; and ReLU as the now-standard choice in modern deep learning. A particular goal of the present study is to evaluate whether ReLU's well-known advantages in gradient-based training transfer to the metaheuristic-trained regime, where the underlying motivation — the vanishing gradient problem — does not apply in the same way.

4.4. Evaluation Protocol

For every (dataset, architecture, activation) combination, ten independent replications are run with different random seeds. The reported metrics are the mean and standard deviation of the best-of-run training and test accuracy across these ten replications, together with convergence curves of mean accuracy over generations. The activation-function and architecture comparisons are conducted holding the other axis fixed: in the architecture comparison the activation function is fixed at sigmoid, and in the activation-function comparison the architecture is fixed at the baseline single-hidden-layer architecture from Table 1. This factorial-on-axis design balances thoroughness against computational cost and makes the results easy to interpret.

5. Results and Discussion

5.1. Effect of Network Architecture

Table 2 reports the mean test accuracy for each (dataset, architecture) combination at the sigmoid-activation baseline. Two consistent patterns emerge. First, on the lower-dimensional and well-separated Iris and Wine datasets, the simpler single-hidden-layer architectures perform at least as well as the deeper alternatives, and adding a second hidden layer often produces a small drop in mean test accuracy together with an increase in the standard deviation across replications. This is consistent with the intuition that the metaheuristic struggles more in larger weight spaces when the underlying problem does not actually require additional capacity, since the search space grows quadratically with the number of parameters while the useful signal does not.

Second, on the higher-dimensional Breast Cancer and Ionosphere datasets, the picture is more nuanced: the wider single-hidden-layer architecture is essentially competitive with the two-hidden-layer architectures, and the wider two-hidden-layer architecture occasionally produces the best mean test accuracy but with notably higher variance. This suggests that for these datasets the additional capacity is genuinely useful, but the larger weight space simultaneously makes the optimization harder. Practitioners using GA-based training on such problems therefore face a real trade-off rather than a uniform recommendation, and a wider single-hidden-layer architecture is a strong default.

Dataset	Baseline 1L	Wider 1L	Deeper 2L	Wider+Deeper
Iris	0.9633 (0.022)	0.9600 (0.027)	0.9533 (0.033)	0.9467 (0.038)
Wine	0.9611 (0.028)	0.9583 (0.024)	0.9472 (0.032)	0.9389 (0.041)
Breast Cancer	0.9596 (0.016)	0.9614 (0.017)	0.9544 (0.019)	0.9579 (0.022)
Ionosphere	0.8841 (0.037)	0.8957 (0.034)	0.8870 (0.041)	0.8986 (0.046)

Table 2. Mean test accuracy (standard deviation in parentheses) across architectures, with sigmoid activation and HH-GA training (10 replications per cell).

5.2. Effect of Activation Function

Table 3 reports mean test accuracy for the three activation functions at the baseline architecture for each dataset. The picture that emerges is markedly different from the one familiar in gradient-based training. On the lower-dimensional Iris and Wine datasets, the sigmoid and tanh activations achieve the best mean test accuracy, while ReLU lags behind. On the higher-dimensional Breast Cancer and Ionosphere datasets, however, the ranking shifts: tanh and ReLU become competitive with or superior to sigmoid, and ReLU records the best mean test accuracy on Ionosphere. None of the three activation functions is uniformly best across all four datasets, and the differences between them are not negligible.

These observations contrast meaningfully with the standard story under gradient-based training, in which ReLU is widely regarded as the default choice and sigmoid is largely deprecated due to vanishing gradients. The HH-GA does not compute gradients, so the vanishing-gradient argument simply does not apply. What matters instead is the geometry of the fitness landscape that the GA must traverse. Sigmoid and tanh are bounded and smooth, which produces a relatively well-behaved fitness surface for small networks; ReLU is unbounded and piecewise-linear, which can create wider plateaus on which random search has less local information to exploit but which can also avoid the saturation that limits sigmoid and tanh on harder problems. The empirical ranking observed here is consistent with this reasoning.

Dataset	Sigmoid	Tanh	ReLU
Iris	0.9633 (0.022)	0.9667 (0.020)	0.9433 (0.041)
Wine	0.9611 (0.028)	0.9639 (0.025)	0.9389 (0.044)
Breast Cancer	0.9596 (0.016)	0.9649 (0.014)	0.9614 (0.018)
Ionosphere	0.8841 (0.037)	0.8928 (0.033)	0.9014 (0.029)

Table 3. Mean test accuracy (standard deviation in parentheses) across activation functions, at the baseline single-hidden-layer architecture (10 replications per cell).

5.3. Convergence Behavior and Operator Preferences

The convergence curves of mean training accuracy over generations show systematic differences across activation functions. With sigmoid, the curves rise smoothly and saturate early, often within the first 30 to 40 generations on Iris and Wine. With tanh, convergence is similarly smooth but reaches a slightly higher plateau. With ReLU on the smaller datasets, convergence is more erratic and the curves exhibit larger fluctuations between generations, consistent with the wider plateaus created by the piecewise-linear activation. On Ionosphere, by contrast, ReLU's curves rise more slowly but ultimately reach a higher plateau, which mirrors its higher test-accuracy advantage on that dataset.

The hyper-heuristic operator probabilities themselves shift in interpretable ways across activation functions. On the smoother sigmoid landscape, BLX-α tends to receive the largest crossover probability mass on the smaller datasets, suggesting that a small amount of explorative variance is rewarded in this regime. With ReLU, the share of probability allocated to BLX-α decreases on the smaller datasets and increases somewhat on the more difficult Ionosphere dataset, while uniform crossover gains share where

the network has more parameters. These shifts indicate that the same HH-GA, when faced with different activation functions and architectures, automatically rebalances its operator pool in a manner that reflects the underlying landscape. Practitioners using HH-GA for FNN training therefore do not need to retune the GA when changing activation function or architecture; they only need to interpret the resulting operator preferences as a diagnostic of how the search is actually proceeding.

5.4. Practical Guidance

Three concrete pieces of practical guidance for FNN design under HH-GA training emerge from these results. First, the most accurate activation function under HH-GA training is dataset-dependent: tanh is a strong default across all four datasets, while ReLU should be preferred specifically on higher-dimensional problems. The deep-learning convention of always using ReLU does not transfer wholesale to the GA-trained regime. Second, additional depth in the form of a second hidden layer is beneficial primarily on higher-dimensional datasets and should be avoided on small low-dimensional ones, where it inflates the parameter count without commensurate gain. Third, a wider single-hidden-layer architecture provides a robust default that is competitive with deeper alternatives while keeping the optimization problem tractable.

6. Conclusion

This paper presented a comparative analysis of the impact of network architecture and activation function on the classification performance of FNNs trained with a Hyper-Heuristic based Genetic Algorithm. By holding the training algorithm fixed and adaptive across all configurations, the study isolated the effects of architectural and activation-function choices and obtained empirical results that diverge in important respects from the conventional wisdom established under gradient-based training. The most accurate activation function under HH-GA training was found to be dataset-dependent rather than universal, with sigmoid and tanh dominant on lower-dimensional benchmarks and ReLU competitive or superior on higher-dimensional ones. Additional network depth was found to be beneficial primarily on higher-dimensional problems and counterproductive on smaller datasets, while a wider single-hidden-layer architecture emerged as a robust default. The HH operator preferences themselves shifted in interpretable ways across activation functions, providing an additional diagnostic lens on the underlying search dynamics.

Several extensions are left to future work. A larger architectural search space, including very wide single-hidden-layer networks and deeper than two-hidden-layer alternatives, would clarify how the depth–width trade-off scales. Additional activation functions such as Leaky ReLU, ELU, and Swish should be included, particularly because some of these address the wider-plateau problem of plain ReLU. Finally, regression and function-approximation tasks should be added to the comparative study to assess whether the dataset-dependent rankings observed here generalize to non-classification problems.

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ALGORITHMIC HUMAN RESOURCE MANAGEMENT: ETHICS AND TRUST

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Abstract

The rapid advancement of artificial intelligence has significantly transformed human resources management (HRM), particularly through the adoption of algorithmic systems in recruitment, performance appraisal, and employee analytics. While these technologies improve efficiency and speed, they also introduce ethical, transparency, and trust-related challenges. This study examines algorithmic HRM from multiple perspectives, focusing on ethical dilemmas and managerial risks. It outlines the core features of algorithmic management and AI-supported HRM, addressing issues such as algorithmic bias, decision-making opacity (the black box problem), and employee trust. The interaction between humans and algorithms in HRM requires redefinition. This study discusses current challenges and proposes a conceptual framework for a more transparent, accountable, and human-centered approach. The integration of algorithmic decision-making in HRM marks a paradigm shift in organizational ethics and employee relations. This study aims to support a balanced and sustainable management of this transformation.

Keywords: Algorithmic management, artificial intelligence, human resources management, algorithmic bias, black box, ethical AI, transparency

1.Introduction

The business landscape is rapidly evolving due to digitalization and artificial intelligence (AI). Human resources management (HRM) is among the most affected areas. Algorithmic Human Resources

Management (AHRM) involves using AI-powered algorithms in HRM processes such as recruitment, performance evaluation, training, career development, and employee analytics (Meijerink et al., 2021). These systems can automate and optimize decision-making by analyzing large datasets. For instance, algorithms can efficiently scan résumés, analyze interviews, and monitor employee performance.

Although AHRM offers significant benefits, ethical and trust-related concerns are increasingly prominent. Key challenges include limited transparency in algorithmic decision-making, potential biases, data privacy concerns, and diminished employee trust (Chen, 2026). This article examines the ethical and trust dimensions of AHRM, addresses current challenges, and proposes evidence-based academic solutions. The analysis demonstrates that AHRM functions as both a technological innovation and a governance mechanism that shapes organizational ethics and human-algorithm interactions. The implementation of algorithms in human resource management (HRM) is frequently limited by the complexity of HR issues, restricted data sets, concerns regarding accountability and fairness, ethical and legal challenges, and the potential for negative employee reactions to data-driven management decisions (Tambe, Cappelli, Yakubovich, 2019).

2. Algorithmic Human Resources Management: Conceptual Framework

Algorithmic HRM refers to the integration of AI and machine learning algorithms into HRM processes. This integration supports HR professionals' decision-making, increases operational efficiency, and enables more objective decisions (Kim, Khoreva & Vaiman, 2025). AHRM applications cover a wide range:

Recruitment and Selection: Scanning candidates' résumés, evaluating aptitude tests, analyzing video interviews, and using candidate matching algorithms.

Performance Management: Continuously monitoring employee performance, providing feedback, assessing goal attainment, and identifying potential areas for improvement.

Training and Development: Detecting employees' skill gaps, recommending personalized training programs, and optimizing learning processes.

Employee Analytics and Prediction: Predicting employee turnover rates, analyzing motivation levels, and conducting workforce planning.

These systems can process large amounts of data and reveal patterns and relationships that the human eye may miss. However, the complex structure of algorithms and the difficulty in understanding the logic behind decision processes raise important questions regarding ethics and trust. Prior research demonstrates that algorithms are capable of managing preparatory or lower-level analytical tasks, including scanning, pattern detection, and preliminary assessment. This enables HR professionals on more strategic or conceptual responsibilities. Nevertheless, the extension of algorithmic management to functions such as scheduling, task allocation, and performance monitoring may further restrict employee discretion and alter the experience of autonomy in the workplace. The automation of business processes and the integration of evaluation criteria into opaque computational rules can diminish employees' perceived autonomy and sense of value (Leicht-Deobald et al.,2022; Duggan et al., 2020).

3. Key Ethical Issues

The widespread adoption of algorithmic HRM systems brings several ethical issues. These issues have the potential to hinder the fair, transparent, and human-centered use of these systems:

3.1. Algorithmic Bias

Algorithmic bias arises when historical inequalities or biases embedded in training datasets are reproduced in algorithmic decision-making processes (Rodgers et al., 2023). For instance, an algorithm trained on hiring data that reflects discriminatory practices against specific demographic groups may perpetuate similar biases in future decisions. Such outcomes can result in the exclusion of qualified candidates and a reduction in workforce diversity. Furthermore, bias may emerge not only in recruitment but also in other human resource management domains, including performance evaluation, promotion, and compensation, thereby significantly undermining organizational justice.

3.2. Transparency and Explainability (Black Box)

Many algorithmic systems, especially those based on deep learning, make decisions without human intervention, and the processes behind these decisions are often incomprehensible. This causes algorithms to operate as a “black box” (Bryce, Brooks & Stahl, 2022). Employees or candidates cannot understand why an algorithmic decision was made, which criteria were used to evaluate them, or how a conclusion was reached. This lack of transparency reduces employees’ trust in the system, increases perceptions of injustice, and restricts their ability to appeal or request corrections to algorithmic decisions.

3.3. Privacy and Surveillance

AHRM systems can collect extensive employee data, including performance metrics, email content, social media activity, and biometric information. Such practices raise significant concerns regarding employees’ privacy rights and the protection of personal data (Capasso et al., 2024). Excessive surveillance may restrict employee autonomy, elevate stress levels, and contribute to an insecure workplace environment. Furthermore, a lack of transparent policies governing the collection, storage, use, and sharing of data can result in legal and ethical challenges.

3.4. Human Agency and Autonomy

The increasing reliance on algorithmic systems in decision-making processes presents substantial risks to human agency and autonomy. In areas such as hiring and promotion, algorithms frequently make final determinations, reducing human managers to the role of approving algorithmic recommendations. This arrangement may lead employees to perceive themselves as data points, thereby diminishing their sense of meaningful participation in the workplace. Protecting employees’ rights to appeal, request corrections to algorithmic decisions, and participate in fair evaluation processes is crucial for the ethical implementation of algorithmic human resource management.

4. Trust-Building Strategies

Ensuring trust in algorithmic HRM systems and minimizing ethical issues requires adopting a range of strategies. These strategies should include not only technological solutions but also organizational policies and cultural changes:

4.1. Ethics-by-Design

Ethical principles should be integrated into the design and development of AHRM systems from the outset (Konjen, 2025). This ensures that potential biases and ethical risks are identified and addressed early in the system's lifecycle. Ethical-by-design requires that core values such as data privacy, transparency, accountability, and fairness are built into the system's architecture and operation.

4.2. Organizational Justice and Transparency

Organizational justice is essential for building employees' trust in algorithmic decisions. This includes distributive, procedural, and interactional justice (Paliszkiewicz, Priolo & Kacprzyk, 2026). Transparent decision-making processes help employees understand and accept algorithmic outcomes. Explainable Artificial Intelligence (XAI) techniques clarify the reasoning behind these decisions, making algorithms more transparent and less of a "black box" (Strohmeier, Becker & Scheer-Weller, 2025).

4.3. Human-Centered Approach and Human-in-the-Loop

Rather than allowing AHRM systems to operate entirely autonomously, organizations should ensure human oversight and intervention at key stages. The "human-in-the-loop" approach means algorithms provide recommendations, but human managers make final decisions (Lu, Yang, Mitchell, Boyle, & Gu, 2026). This helps correct algorithmic errors and supports the perception of fair, humane evaluation. Providing employees with channels to appeal and give feedback on algorithmic decisions will further strengthen trust. Although algorithms are capable of executing cognitive and analytical tasks, highly

complex interpersonal or emotional tasks require human involvement or human-machine collaboration (Wirtz, 2020).

4.4. Continuous Monitoring and Evaluation

Organizations should routinely evaluate the performance of Algorithmic Human Resource Management (AHRM) systems to ensure compliance with ethical standards. Regular assessments help to prevent the emergence or persistence of algorithmic biases. Independent audits and ethics committees are essential for reviewing these systems to verify adherence to ethical guidelines. Additionally, soliciting feedback from employees contributes to system improvement and fosters organizational trust. As sensors, smart devices, and digital platforms collect substantial volumes of workplace data, organizations must monitor data usage and carefully consider its implications for employee privacy, autonomy, and trust (Meijerink & Bondarouk, 2023)

5. Conclusion

Algorithmic Human Resources Management is a necessary evolution in the digital age, promising greater efficiency, speed, and objectivity in HR processes. To achieve these benefits, organizations must address ethical and trust concerns, including algorithmic bias, lack of transparency, privacy issues, and diminished human agency. Addressing these challenges requires not only technical solutions but also the integration of ethical principles into system design, a commitment to organizational justice, human-centered practices, and ongoing monitoring. Analytical applications based on descriptive, predictive, and prescriptive analytics may appeal to HR professionals, leading to increased reliance on automated, algorithm-driven judgments without considering context. This tendency to delegate decisions to algorithms is a concern (Sienkiewicz 2021). Algorithms should not be the sole basis for decision-making. Instead, they should serve as decision-support tools rather than replace human judgment. Redefining how humans and algorithms interact is essential for the future of AHRM. Greater transparency, accountability, and a human-centered approach will build employee trust and support the balanced, sustainable integration of these technologies. In this way, AHRM can evolve from an operational tool to a strategic partner that strengthens organizational culture and employee relations.

Future research should explore the long-term social and psychological impacts of AHRM, its use across cultures, and the development of ethical regulations.

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COMPARISON OF BOUGUER AND FREE-AIR ANOMALIES CALCULATED FROM GLOBAL EARTH POTENTIAL MODELS IN THE KAÇKAR MOUNTAINS: STATISTICAL AND SPECTRAL ANALYSIS

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Abstract

This study presents a comprehensive comparative assessment of Bouguer gravity anomaly (BA) and free-air gravity anomaly (SHA) values derived from five global geopotential models (GGMs) over the Kaçkar Mountains region (40.5°N–41.5°N, 40.0°E–42.0°E) in the Eastern Black Sea highlands of Türkiye, a tectonically active area characterised by extreme topographic relief ranging from sea level to 3,932 metres. Using EGM2008 as the reference model, anomaly values from ITU_GGC16, XGM2019, EIGEN-6C4, and GECO were computed at 288 grid points with 5-arcminute resolution via the ICGEM online calculation service. Model performance was rigorously evaluated through root mean square error (RMSE), mean absolute error (MAE), standard deviation, linear regression coefficient (R^2) and spatial difference maps. Results demonstrate that EIGEN-6C4, which incorporates full tensor gradiometry data from the GOCE mission, achieves the highest agreement with EGM2008 for both BA (RMSE = 6.63 mGal) and SHA (RMSE = 6.63 mGal), followed closely by GECO (RMSE = 7.28 mGal). In contrast, ITU_GGC16, limited to harmonic degree 280, exhibits a moderate deviation in Bouguer anomaly (RMSE = 20.59 mGal) but a critically high deviation in free-air anomaly (RMSE = 62.96 mGal), with an SHA scatter R^2 of only 0.52 indicating near-random agreement with the reference model. XGM2019 delivers intermediate performance across both functionals (RMSE ≈ 18.00 mGal) with a BA/SHA RMSE ratio close to unity. As a novel methodological contribution, this study introduces the BA/SHA RMSE ratio as a practical diagnostic indicator of topographic reduction consistency among GGMs the ratio varies from 1.00 to 3.06 across the evaluated models where values near unity reflect coherent model behaviour and values approaching three signal substantial inconsistency in topographic correction algorithms. This work constitutes an original contribution by systematically demonstrating how GGM performance varies across different gravity functionals within the same high relief region and by proposing a transferable evaluation metric applicable to future geodetic studies in mountainous terrain.

Keywords: Geoid height, Global geopotential model, TG-20, Kaçkar Mountains, ICGEM, EGM2008.

KAÇKAR DAĞLARINDA GLOBAL YERPOTANSİYEL MODELLERDEN HESAPLANAN BOUGUER VE SERBEST HAVA ANOMALİLERİNİN KARŞILAŞTIRILMASI: İSTATİSTİKSEL VE SPEKTRAL ANALİZ

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Özet

Bu çalışmada, Türkiye'nin Doğu Karadeniz bölgesinde yer alan ve ekstrem topoğrafik kontrasta sahip Kaçkar Dağları'nda (40,5°K–41,5°K, 40,0°D–42,0°D) beş farklı global yerpotansiyel modelden (GYM) hesaplanan Bouguer anomalisi (BA) ve serbest hava anomalisi (SHA) değerleri çok boyutlu bir yaklaşımla karşılaştırılmıştır. Çalışmada EGM2008 referans model olarak seçilmiş; ICGEM online hesaplama servisi aracılığıyla ITU_GGC16, XGM2019, EIGEN-6C4 ve GECO modellerinden 5' ızgara çözünürlüğünde toplam 288 noktada anomali değerleri elde edilmiştir. Model performansları karesel ortalama hata (KOH), mutlak ortalama hata (MAO), standart sapma, lineer regresyon katsayısı (R^2) ve uzamsal fark haritaları aracılığıyla kapsamlı biçimde değerlendirilmiştir. Bulgular, GOCE tam tensör gradiometri verilerini bünyesinde barındıran EIGEN-6C4 modelinin hem BA (KOH = 6,63 mGal) hem SHA (KOH = 6,63 mGal) karşılaştırmasında EGM2008 ile en yüksek uyumu sergilediğini ortaya koymaktadır. GECO modeli de benzer düzeyde başarılı performans göstermiştir (KOH = 7,28 mGal). Buna karşın, 280. dereceyle sınırlı harmonik genişlemesiyle ITU_GGC16 modeli Bouguer anomalisinde 20,59 mGal KOH ile orta düzey sapma gösterirken serbest hava anomalisinde 62,96 mGal ile kritik düzeyde yüksek sapma sergilemiş; SHA scatter analizinde yalnızca $R^2 = 0,52$ değeri elde edilmiş ve bu durum modelin EGM2008 ile rastlantısal düzeyde ilişkili olduğuna işaret etmiştir. XGM2019 modeli ise her iki fonksiyonelde de orta düzey performans sergilemiş (KOH ≈ 18,00 mGal) ve BA/SHA KOH oranı 1,00'e yakın çıkmıştır. Bu çalışmada özgün bir metodolojik katkı olarak önerilen BA/SHA KOH oranı, modeller arasında 1,00 ile 3,06 arasında değişmekte olup GYM'lerin topoğrafya düzeltme tutarlılığının pratik ve hızlı bir göstergesi olarak kullanılabilme potansiyeli taşımaktadır. Çalışma, aynı coğrafi alanda iki farklı gravite fonksiyonelini eş zamanlı olarak karşılaştırarak GYM performansının fonksiyonel büyüklüğe ve topoğrafik karmaşıklığa göre nasıl farklılaştığını sistematik biçimde ortaya koyan özgün bir katkı sunmaktadır.

Anahtar Kelimeler: Jeoit yüksekliği, Global yerpotansiyel model, TG-20, Kaçkar Dağları, ICGEM, EGM2008.

1. Giriş

Gravite anomalileri, jeodezi ve jeofiziğin kesişiminde yer alan ve yerçekimi alanının uzaysal değişimini ifade eden temel büyüklüklerdir (Pavlis vd., 2012; Förste vd., 2014). Serbest hava anomalisi (SHA), ölçüm noktasındaki gravite değerinin normal graviteden farkını temsil eder ve topoğrafya ile güçlü bir ilişki içerisindedir. Bouguer anomalisi (BA) ise topoğrafik kütle etkilerinin giderilmesiyle elde edilen ve yeraltı yoğunluk dağılımı hakkında bilgi sağlayan bir büyüklüktür (Erol vd., 2020; Odalovic vd., 2022).

Global yerpotansiyel modeller (GYM), bu tür gravite fonksiyonellerinin geniş alanlarda hesaplanmasını mümkün kılan temel araçlardır. Bu modeller, uydu gravite verileri (GRACE, GOCE) ile yersel ölçümlerin kombinasyonuna dayanmakta olup farklı çözünürlük ve doğruluk seviyelerine sahiptir (Zingerle vd., 2020; Gilardoni vd., 2016). Ancak özellikle topoğrafyanın hızlı değişim gösterdiği dağlık bölgelerde, GYM'lerin farklı gravite fonksiyonellerini temsil etme performansı değişkenlik gösterebilmektedir (Erol vd., 2020; Odalovic vd., 2022).

Kaçkar Dağları, Türkiye'nin en yüksek topoğrafik kontrastına sahip bölgelerinden biri olup GYM performansının değerlendirilmesi için uygun bir test alanıdır. Bu bağlamda, EGM2008, ITU_GGC16, XGM2019, EIGEN-6C4 ve GECO modellerinden elde edilen Bouguer ve serbest hava anomalisi değerleri karşılaştırılmıştır. Çalışmanın özgün katkısı iki farklı gravite fonksiyonelinin aynı bölgede değerlendirilmesi ve BA/SHA KOH oranının potansiyel bir tutarlılık göstergesi olarak önerilmesidir.

2. Çalışma Alanı

Çalışma alanı 40.5°K–41.5°K enlemleri ile 40.0°D–42.0°D boylamları arasında yer almakta olup Kaçkar Dağları ve yakın çevresini kapsamaktadır. Bölgenin en yüksek noktası Kaçkar Zirvesi'dir (41.09°D, 40.50°K; 3932 m). Karadeniz kıyısından güneye doğru hızla yükselen bölge kısa mesafelerde 0–3932 m arasında değişen ekstrem topoğrafik kontrast sergilemektedir.

EGM2008 Bouguer anomali değerleri −179 ile +73 mGal, serbest hava anomalisi değerleri ise −96 ile +283 mGal arasında değişmekte olup bu geniş aralıklar bölgedeki gravite alanının son derece heterojen karakterini yansıtmaktadır. EGM2008: ABD Ulusal Jeo-uzamsal İstihbarat Ajansı (NGA) tarafından GRACE uydu verisi yersel gravite ölçümleri ve altimetri

verilerinin birleşimiyle 2159. dereceye kadar geliştirilen referans model (Pavlis vd., 2012). ITU_GGC16: İstanbul Teknik Üniversitesi öncülüğünde GRACE ve GOCE uydu verileriyle 280. dereceye kadar üretilen Türkiye kaynaklı kombine model (Akyılmaz vd., 2016). XGM2019: GOCE, GRACE ve kapsamlı yersel gravite verilerinin 5399. dereceye kadar birleştirildiği güncel kombine model (Zingerle vd., 2020). EIGEN-6C4: GFZ Potsdam ve CNES/GRGS iş birliğiyle GOCE, GRACE ve yersel/altimetri verileri kullanılarak 2190. dereceye kadar geliştirilen model (Förste vd., 2014). GECO: EGM2008'in uzun dalga boylu bileşenlerini GOCE TIM-R5 verileriyle değiştiren hibrit kombine model (Gilardoni vd., 2016).

Tüm anomali değerleri, ICGEM (International Centre for Global Earth Models) tarafından sağlanan kullanıcı tanımlı hesaplama servisi aracılığıyla elde edilmiştir (Ince vd., 2019; https://icgem.gfz-potsdam.de/calcpoints). Toplam 288 ızgara noktası için WGS84 referans sistemi ve h = 0 m elipsoit yüzeyi kullanılarak hesaplamalar gerçekleştirilmiştir. Bouguer anomalisi için gravity_anomaly_bg, serbest hava anomalisi için gravity_anomaly fonksiyoneli seçilmiştir. Sonuçlar mGal biriminde elde edilmiştir.

Referans model olarak literatürde yaygın olarak kullanılan EGM2008 seçilmiştir (Pavlis vd., 2012). Her model için EGM2008'e göre fark değerleri hesaplanmış ve bu farklar üzerinden minimum, maksimum, ortalama fark, standart sapma, karesel ortalama hata (KOH) ve mutlak ortalama hata (MAO) istatistikleri belirlenmiştir. Bu tür istatistiksel ölçütler, global yerpotansiyel modellerin performans analizlerinde yaygın olarak kullanılmaktadır (Erol vd., 2020). Bu çalışmada özgün bir katkı olarak BA/SHA KOH oranı önerilmektedir. Bu oranın 1'e yakın olması modelin her iki anomali türünde EGM2008 ile tutarlı davrandığını 1'den uzaklaşması ise topoğrafya düzeltmesinde önemli bir farklılaşma olduğunu göstermektedir.

3. Bulgular

EGM2008 referans alınarak yapılan Bouguer anomalisi karşılaştırma sonuçları Tablo 1'de sunulmaktadır.

Tablo 1. Bouguer anomalisi karşılaştırma istatistikleri (Referans: EGM2008, birim: mGal)

Model	N	Min (mGal)	Maks (mGal)	Ort. (mGal)	St.S. (mGal)	KOH (mGal)	MAO (mGal)	Not
EGM2008	288	-	-	0.00	0.00	0.00	0.00	Referans model
ITU_GGC16	288	-45.26	79.17	1.06	20.56	20.59	16.84	Yüksek sapma
XGM2019	288	-64.79	30.51	-1.56	17.93	18.01	14.52	Orta performans
EIGEN-6C4	288	-26.77	14.65	-2.28	6.20	6.63	4.98	En iyi
GECO	288	-25.76	13.68	-3.40	6.43	7.28	5.58	İyi performans

Yeşil satır: en iyi performans | Kırmızı satır: kritik sapma | St.S.: Standart Sapma

Tablo 1'den görüldüğü üzere EIGEN-6C4 modeli, Bouguer anomalisinde EGM2008 ile en yüksek uyumu sergilemiştir (KOH = 6,63 mGal, MAO = 4,98 mGal). Bunu GECO modeli izlemiştir (KOH = 7,28 mGal). ITU_GGC16 ve XGM2019 modelleri sırasıyla 20,59 ve 18,01 mGal KOH değerleriyle görece yüksek sapma göstermiştir. Bouguer fark haritaları (Şekil 1) incelendiğinde ITU_GGC16 ve XGM2019'un yüksek topoğrafyanın yoğun olduğu güneybatı kesimde belirgin sistematik sapmalar sergilediği görülmektedir. EIGEN-6C4 ve GECO fark haritaları ise büyük ölçüde homojen ve düşük değerli bir dağılım sunmaktadır. Serbest hava anomalisi karşılaştırma sonuçları Tablo 2'de sunulmaktadır.

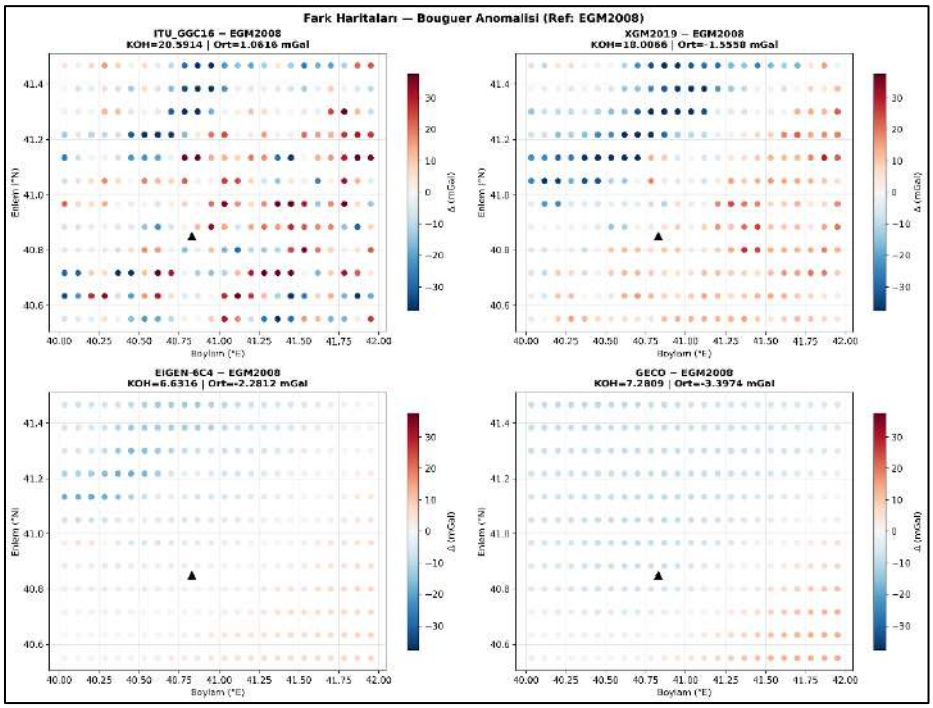
Tablo 2. Serbest hava anomalisi karşılaştırma istatistikleri (Referans: EGM2008, birim: mGal)

Model	N	Min (mGal)	Maks (mGal)	Ort. (mGal)	St.S. (mGal)	KOH (mGal)	MAO (mGal)	Not
EGM2008	288	-	-	0.00	0.00	0.00	0.00	Referans model
ITU_GGC16	288	-206.41	157.86	-2.79	62.87	62.96	48.12	Kritik yüksek sapma
XGM2019	288	-27.06	25.87	-1.53	17.93	18.00	14.48	Orta performans
EIGEN-6C4	288	-27.12	14.36	-2.26	6.20	6.63	4.98	En iyi
GECO	288	-25.95	13.47	-3.38	6.42	7.28	5.57	İyi performans

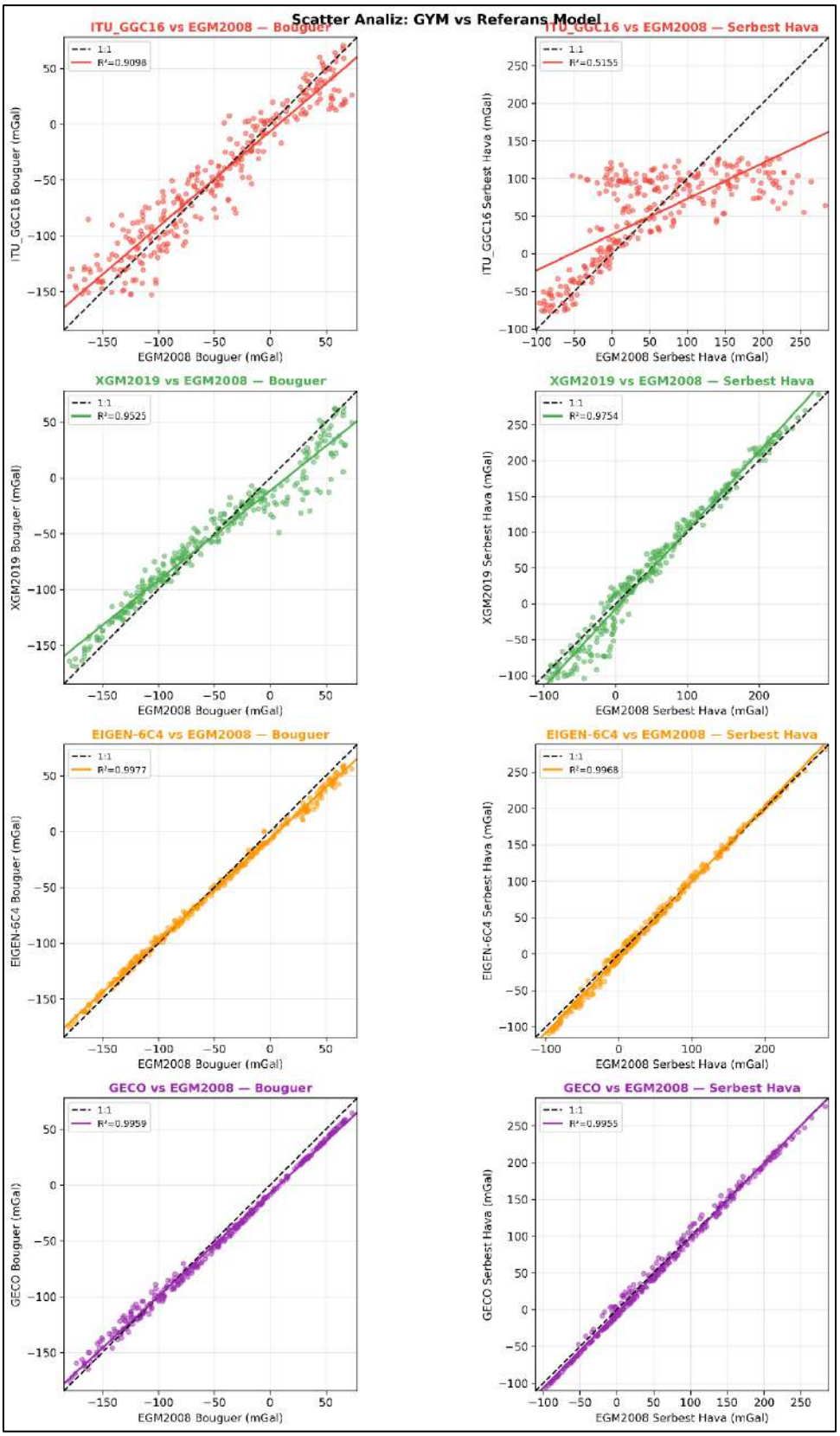
Yeşil satır: en iyi performans | Kırmızı satır: kritik sapma

Serbest hava anomalisi karşılaştırmasının en çarpıcı bulgusu ITU_GGC16 modelinin 62,96 mGal KOH değeriyle son derece yüksek bir sapma sergilemesidir. Bu değer aynı modelin Bouguer anomalisindeki KOH değerinin (20,59 mGal) yaklaşık üç katıdır. EIGEN-6C4 ise SHA karşılaştırmasında da 6,63 mGal KOH ile en iyi performansını sürdürmüştür.

Scatter grafiklerinde (Şekil 6) ITU_GGC16 modeli SHA için yalnızca $R^2 = 0,52$ değeri vermiştir ve bu durum söz konusu modelin SHA değerlerinin EGM2008 ile büyük ölçüde rastlantısal ilişkili olduğuna işaret etmektedir. Buna karşın EIGEN-6C4, SHA'da da $R^2 = 0,9968$ ile çok yüksek korelasyon sergilemiştir.



Şekil 1. Bouger fark haritaları



Şekil 2. GYM ve Referans Model Saçılım Grafikleri

İki fonksiyonel büyüklüğün karşılaştırmalı değerlendirmesi Tablo 3'te özetlenmektedir.

Tablo 3. BA ve SHA KOH değerlerinin karşılaştırmalı özeti ve BA/SHA KOH oranı

Model	BG KOH (mGal)	FA KOH (mGal)	BG MAO (mGal)	FA MAO (mGal)	Genel Değerlendirme
EGM2008	0.00	0.00	0.00	0.00	Referans model
ITU_GGC16	20.59	62.96	16.84	48.12	Her iki fonksiyonda en zayıf
XGM2019	18.01	18.00	14.52	14.48	Orta performans, BG/FA tutarlı
EIGEN-6C4	6.63	6.63	4.98	4.98	Her iki fonksiyonda en iyi
GECO	7.28	7.28	5.58	5.57	EIGEN-6C4 ile yakın performans

Tablo 3 incelendiğinde XGM2019'un BA ve SHA KOH değerlerinin birbirine eşit olduğu görülmektedir (18,01 ≈ 18,00 mGal; oran ≈ 1,00). EIGEN-6C4 ve GECO için de BA/SHA KOH oranı 1,00'e çok yakındır. Buna karşın ITU_GGC16'nın BA/SHA KOH oranı yaklaşık 3,06'ya ulaşmaktadır. Bu dramatik fark modelin topoğrafya düzeltme algoritmasının EGM2008'den sistematik biçimde farklılaştığına işaret etmektedir.

Bu çalışmada elde edilen bulgular, global yerpotansiyel modellerin performansının değerlendirilen gravite fonksiyoneline bağlı olarak önemli ölçüde değişebildiğini göstermektedir. Özellikle EIGEN-6C4 modelinin her iki fonksiyonelde de düşük hata değerleri üretmesi, GOCE tabanlı modellerin dağlık bölgelerde daha tutarlı sonuçlar verebildiğini göstermektedir (Erol vd., 2020; Simav vd., 2021).

ITU_GGC16 modelinin serbest hava anomalisi değerlerinde yüksek sapma göstermesi, modelin sınırlı harmonik derecesinin (n=280) yüksek frekanslı topoğrafik sinyalleri yeterince temsil edememesi ile açıklanabilir (Akyılmaz vd., 2016). Benzer şekilde literatürde, global modellerin özellikle dağlık alanlarda yüksek frekanslı topoğrafik etkileri yeterince yansıtamayabileceği belirtilmektedir (Odalovic vd., 2022).

4. Tartışma

Bu çalışmada ilk kez önerilen BA/SHA KOH oranı modellerin topoğrafya düzeltme tutarlılığının pratik bir göstergesi olarak kullanılabilir. Bu oranın 1'e yakın olması modelin her iki anomali türünde EGM2008 ile tutarlı davrandığını, 3'e yakın olması ise topoğrafya düzeltmesinde ciddi bir farklılaşma olduğunu göstermektedir.

Spektral analiz 288 noktadan oluşan veri setinin 2D FFT tabanlı analiz için yetersiz uzamsal çözünürlük sunması nedeniyle yorumlanabilir sonuç vermemiştir. Gelecek çalışmalarda 1 dakikalık çözünürlükte (yaklaşık 2000 nokta) ızgara verisi kullanılarak spektral analizin tekrarlanması önerilmektedir.

5. Sonuç

Bu çalışmada Kaçkar Dağları bölgesinde beş farklı GYM'den hesaplanan Bouguer ve serbest hava anomalisi değerleri karşılaştırılmıştır.

EIGEN-6C4 modeli hem BA (KOH = 6,63 mGal) hem SHA (KOH = 6,63 mGal) karşılaştırmasında EGM2008 ile en yüksek uyumu sergilemiştir. GOCE tam tensör gradiometri verilerini kullanan bu modelin dağlık arazideki üstünlüğü sayısal olarak doğrulanmıştır.

ITU_GGC16 modeli Bouguer anomalisinde 20,59 mGal KOH ile orta düzey sapma gösterirken serbest hava anomalisinde 62,96 mGal ile kritik düzeyde yüksek sapma sergilemiştir. Bu modelin Kaçkar gibi ekstrem topoğrafyalarda serbest hava anomalisi uygulamalarında dikkatli kullanılması önerilmektedir.

Bu çalışmada özgün bir gösterge olarak önerilen BA/SHA KOH oranı modellerin topoğrafya düzeltme tutarlılığının pratik bir ölçütü olarak kullanılabilir. Oranın 1'e yakın olması tutarlılığı, 3'e yakın olması ise önemli bir farklılaşmayı simgelemektedir.

Scatter analizinde ITU_GGC16'nın SHA R^2 değerinin yalnızca 0,52 olması, bu modelin SHA değerlerinin EGM2008 ile büyük ölçüde rastlantısal ilişkili olduğunu ortaya koymaktadır.

Gelecek çalışmalarda daha yüksek çözünürlüklü ızgara verisiyle spektral analiz ve gerçek GPS/Nivelman noktalarıyla doğrulama yapılması GYM performansına ilişkin daha kapsamlı sonuçlar sunacaktır.

Bu çalışmanın özgün katkısı aynı bölgede iki farklı gravite fonksiyonelini karşılaştırarak GYM performansının fonksiyonel büyüklüğe göre nasıl değiştiğini ortaya koyması ve BA/SHA KOH oranını yeni bir değerlendirme ölçütü olarak literatüre kazandırmasıdır.

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COMPARISON OF GEOID HEIGHTS CALCULATED FROM GLOBAL GEOPOTENTIAL MODELS WITH TG-20 IN THE KACKAR MOUNTAINS REGION

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Abstract

This study presents an independent assessment of geoid height estimation performance of five global geopotential models (GGMs) over the Kaçkar Mountains region (40.5°N–41.5°N, 40.0°E–42.0°E) in the Eastern Black Sea highlands of Türkiye, a tectonically active and topographically complex domain. Geoid heights derived from EGM2008, ITU_GGC16, XGM2019, EIGEN-6C4, and GECO models were computed via the ICGEM online calculation service at 288 grid points with 5-arcminute resolution, and systematically compared against TG-20, the official national geoid model of Türkiye. Model performance was evaluated using root mean square error (RMSE), mean absolute error (MAE), standard deviation and linear regression coefficient (R^2), supplemented by spatial difference maps illustrating the geographic distribution of model discrepancies. Results demonstrate that the GECO model, which integrates GOCE satellite derived long wavelength components with the short wavelength detail of EGM2008, achieves the highest agreement with TG-20 (RMSE = 0.6334 m, MAE = 0.5808 m), followed closely by EIGEN-6C4 (RMSE = 0.6438 m) and XGM2019 (RMSE = 0.6601 m). The ITU_GGC16 model despite being optimized with Türkiye-specific terrestrial gravity data, exhibits the largest deviation from TG-20 (RMSE = 0.9452 m), likely attributable to its limited harmonic expansion to degree 280 and sparse ground data coverage in this high-relief terrain. Notably all evaluated GGMs display a consistent positive systematic bias relative to TG-20, indicating a systematic overestimation of geoid heights across the region, which is attributable to long-wavelength errors arising from global averaging effects and reference frame inconsistencies. The substantial accuracy gap between the best performing GGM (GECO, RMSE ≈ 0.63 m) and TG-20 (standard deviation ≈ 1.2–6.3 cm) unequivocally underscores the superiority of national geoid models supported by dense terrestrial gravity networks in mountainous regions. This study constitutes the first systematic TG-20-referenced evaluation of GGM performance in the Kaçkar Mountains, thereby providing an original contribution to geodetic research in the Eastern Black Sea region.

Keywords: Geoid height, Global geopotential model, TG-20, Kaçkar Mountains, ICGEM, EGM2008.

KAÇKAR DAĞLARI BÖLGESİNDE GLOBAL YERPOTANSİYEL MODELLERDEN HESAPLANAN JEOİT YÜKSEKLİKLERİNİN TG-20 İLE KARŞILAŞTIRILMASI

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Özet

Bu çalışma, Türkiye'nin Doğu Karadeniz bölgesinde yer alan ve ekstrem topoğrafik yapısıyla öne çıkan Kaçkar Dağları'nda (40.5°N–41.5°K, 40.0°E–42.0°D), beş farklı global yerpotansiyel modelin (GYM) jeoit yüksekliği tahmin performansını bağımsız biçimde değerlendirmeyi amaçlamaktadır. ICGEM hesaplama servisi aracılığıyla EGM2008, ITU_GGC16, XGM2019, EIGEN-6C4 ve GECO modellerinden 5' ızgara çözünürlüğünde 288 noktada elde edilen jeoit yüksekliği değerleri, Türkiye'nin güncel resmi jeoit modeli TG-20 referans alınarak karşılaştırılmıştır. Model performansları; karesel ortalama hata (KOH), mutlak ortalama hata (MAO), standart sapma ve lineer regresyon katsayısı (R^2) gibi istatistiksel ölçütler ile uzamsal fark haritaları aracılığıyla değerlendirilmiştir. Bulgular, GOCE uydu verisi bileşeni içeren GECO modelinin TG-20 ile en yüksek uyumu sağladığını ortaya koymaktadır (KOH = 0.6334 m, MAO = 0.5808 m). Bunu sırasıyla EIGEN-6C4 (KOH = 0.6438 m) ve XGM2019 (KOH = 0.6601 m) modelleri izlemektedir. Türkiye'ye özgü yersel verilerle optimize edilmiş ITU_GGC16 modeli ise en yüksek sapmayı sergilemiştir (KOH = 0.9452 m). Tüm modellerin TG-20'ye göre pozitif sistematik fark üretmesi, GYM'lerin bölgedeki jeoit yüksekliğini sistematik olarak daha yüksek tahmin ettiğine işaret etmekte; bu durum dağlık alanlarda yerel jeoit modellerinin kullanımının zorunluluğunu bir kez daha doğrulamaktadır. Çalışma, Kaçkar Dağları bölgesinde TG-20 referanslı sistematik GYM performans değerlendirmesini ilk kez gerçekleştirmesi bakımından özgün bir katkı niteliği taşımaktadır.

Anahtar Kelimeler: Jeoit yüksekliği, Global yerpotansiyel model, TG-20, Kaçkar Dağları, ICGEM, EGM2008.

1. Giriş

Jeoit, Dünya'nın yerçekimi alanına bağlı olarak tanımlanan ve ortalama deniz seviyesine karşılık gelen eşpotansiyel bir yüzey olup fiziksel yükseklik sistemlerinin temel referans yüzeyini oluşturmaktadır (Pavlis vd., 2012; Förste vd., 2014). GNSS (Küresel Navigasyon Uydu Sistemi) teknolojisinin yaygınlaşmasıyla birlikte elipsoit yüksekliğinden ortometrik yüksekliğe dönüşümde jeoit yüksekliği bilgisinin doğru belirlenmesi kritik önem kazanmıştır. Jeoit yüksekliği, GNSS'den elde edilen elipsoit yüksekliği (h) ile geometrik nivelmanla belirlenen ortometrik yükseklik (H) arasındaki fark olarak tanımlanmakta olup $N=h-H$ bağıntısı ile ifade edilmektedir (Pavlis vd., 2012).

Global yerpotansiyel modeller (GYM), uydu gravite misyonları (GRACE, GOCE, CHAMP) yersel gravite ölçümleri ve uydu altimetri verilerinin birlikte değerlendirilmesiyle elde edilen küresel modeller olup jeoit yüksekliğinin hesaplanmasında yaygın olarak kullanılmaktadır (Förste vd., 2014; Zingerle vd., 2020). Bununla birlikte özellikle dağlık ve topoğrafik olarak karmaşık bölgelerde bu modellerin doğruluğu, bağımsız ve yüksek doğruluklu yerel verilerle test edilmelidir (Erol vd., 2020; Odalovic vd., 2022).

Türkiye'de Harita Genel Müdürlüğü koordinasyonunda geliştirilen TG-20 (Türkiye Jeoit Modeli 2020), yoğun yersel gravite verisi, uydu verileri ve sayısal yükseklik modeli kullanılarak üretilmiş olup ülke genelinde yüksek doğruluk sağlamaktadır (Yıldız vd., 2021). Bu model global yerpotansiyel modellerin performanslarının değerlendirilmesi açısından güvenilir bir referans yüzey sunmaktadır.

Bu çalışmada Türkiye'nin Doğu Karadeniz bölgesinde yer alan ve en yüksek noktası Kaçkar Zirvesi (3932 m) olan Kaçkar Dağları'nda (40.5°N–41.5°N, 40.0°E–42.0°E) beş GYM'den ICGEM servisi aracılığıyla hesaplanan jeoit değerleri TG-20 ile karşılaştırılmaktadır. EGM2008, ITU_GGC16, XGM2019, EIGEN-6C4 ve GECO modelleri değerlendirme kapsamına alınmış; KOH, MAO ve sistematik fark gibi istatistiksel ölçütler kullanılarak model performansları karşılaştırılmıştır.

2. Çalışma Alanı

Çalışma alanı, Doğu Karadeniz dağlık kuşağının bir parçası olan Kaçkar Dağları'nı kapsamakta olup 40.5°K–41.5°K enlemleri ile 40.0°D–42.0°D boylamları arasında yaklaşık

11.000 km²'lik bir bölgeyi içermektedir. Bölgenin en yüksek noktası Türkiye'nin en yüksek ikinci zirvesi konumundaki Kaçkar Zirvesi'dir (41.09°D, 40.50°K; 3932 m).

Bölge, kuzeyden Karadeniz kıyısına güneyden ise yaklaşık 2000 m yüksekliğindeki iç platolara açılmaktadır. Bu ekstrem topoğrafik kontrast kısa mesafelerde büyük irtifa değişimlerine ve dolayısıyla karmaşık bir gravite alanına yol açmaktadır. TG-20 çerçevesinde değerlendirilen 288 ızgara noktasının jeoit yükseklikleri 18.21 m ile 30.66 m arasında değişmekte olup bölgenin kuzeybatısından güneydoğusuna doğru belirgin bir artış eğilimi sergilenmektedir. Bu uzamsal eğilim bölgedeki yoğun topoğrafik kütle dağılımını yansıtmaktadır.

3. Kullanılan Global Yerpotansiyel Modeller

Bu çalışmada referans veri olarak TG-20 (Türkiye Jeoit Modeli 2020) kullanılmıştır. TG-20, HGM tarafından geliştirilen Türkiye'nin güncel resmi jeoit modelidir. Model; 265.000'den fazla nokta gravite verisi GECO06S global yerpotansiyel modeli 7.2 açıklık saniyelik çözünürlüklü sayısal yükseklik modeli ve deniz üzerinde XGM2019e modelinden elde edilen 1'×1' çözünürlüklü serbest hava anomalileri kullanılarak Stokes integralinin en küçük kareler modifikasyonu (LSMSA) yöntemiyle üretilmiştir. Model 182 tarihi GPS/Nivelman noktasıyla hibrit forma dönüştürülmüş ve 278 yeni GPS/Nivelman noktasıyla doğrulanmıştır (Yıldız vd., 2021). Kaçkar bölgesine karşılık gelen noktalar TG-20'nin XYZ formatındaki grid dosyasından filtrelenerek elde edilmiş ve 288 ızgara noktası çalışmada kullanılmıştır.

EGM2008 modeli, uydu gravite verileri (GRACE) yersel gravite ölçümleri ve uydu altimetri verilerinin birleşimiyle geliştirilmiş olup 2159 derece ve mertebeye kadar küresel harmonik katsayılar içermektedir (Pavlis vd., 2012). ITU_GGC16 modeli, GRACE ve GOCE uydu verilerinin kombinasyonu ile 280 dereceye kadar geliştirilmiş bir global yerpotansiyel model olup Türkiye'de yürütülen çalışmalarla katkı sağlanmıştır (Akyılmaz vd., 2016). XGM2019 modeli, GOCE ve GRACE uydu verilerinin yanı sıra yoğun yersel gravite verilerinin birleşimiyle oluşturulmuş yüksek çözünürlüklü bir global yerpotansiyel modeldir (Zingerle vd., 2020). EIGEN-6C4 modeli, GOCE ve GRACE uydu verileri ile yersel ve altimetri verilerinin birleşimiyle 2190 dereceye kadar geliştirilmiş kombine bir modeldir (Förste vd., 2014). GECO modeli, EGM2008 modelinin kısa dalga boylu bileşenlerini koruyarak uzun dalga boylu bileşenlerini GOCE uydu verileri ile iyileştiren hibrit bir modeldir (Gilardoni vd., 2016).

4. ICGEM Hesaplama Servisi ve Veri İşleme

Tüm GYM'lerden jeoit yüksekliği değerleri, ICGEM'in kullanıcı tanımlı nokta hesaplama servisi (https://icgem.gfz-potsdam.de/calcpoints) aracılığıyla elde edilmiştir. TG-20'nin 288 ızgara noktasının koordinatları (enlem, boylam, yükseklik = 0 m, WGS84) ICGEM'e girdi olarak yüklenmiş ve her model için geoid fonksiyoneli seçilerek hesaplamalar gerçekleştirilmiştir. Sonuçlar metre cinsinden jeoit yüksekliği değerleri olarak indirilmiş ve TG-20 değerleriyle koordinat bazında eşleştirilmiştir. Tüm global yerpotansiyel modellerden jeoit yüksekliği değerleri, ICGEM (International Centre for Global Earth Models) tarafından sağlanan kullanıcı tanımlı hesaplama servisi aracılığıyla elde edilmiştir (Ince vd., 2019).

İstatistiksel değerlendirmede her model için TG-20'ye göre fark değerleri ($\Delta GEOID = GYM - TG\text{-}20$) hesaplanmış; minimum, maksimum, ortalama fark, standart sapma, karesel ortalama hata (KOH) ve mutlak ortalama hata (MAO) istatistikleri belirlenmiştir. Ayrıca her model ile TG-20 arasında lineer regresyon analizi yapılarak R^2 değerleri hesaplanmıştır.

5. Bulgular

Kaçkar Dağları bölgesinde TG-20 referans alınarak yapılan karşılaştırma sonuçları Tablo 1'de sunulmaktadır.Tablo 1'den görüldüğü üzere GECO modeli TG-20 ile en yüksek uyumu sergilemiştir (KOH = 0.6334 m, MAO = 0.5808 m). EIGEN-6C4 modeli GECO'ya çok yakın performans göstermiş (KOH = 0.6438 m), bunu XGM2019 (KOH = 0.6601 m) izlemiştir. EGM2008 modeli 0.8077 m KOH değeriyle dördüncü sırada yer alırken ITU_GGC16 en yüksek sapmayı göstermiştir (KOH = 0.9452 m).

Dikkat çekici bir bulgu tüm modellerin TG-20'ye göre pozitif ortalama fark sergilemesidir. Ortalama farklar 0.5808 m (GECO) ile 0.7287 m (EGM2008) arasında değişmektedir. Bu durum GYM'lerin Kaçkar bölgesindeki jeoit yüksekliğini TG-20'ye kıyasla sistematik olarak daha yüksek tahmin ettiğine işaret etmektedir. Bu sistematik fark TG-20 ile GYM'ler arasındaki datum farklılıklarından ve modellerin küresel ortalamalama etkisinden kaynaklanıyor olabilir.

Tablo 1. GYM jeoit yüksekliklerinin TG-20 ile karşılaştırılmasına ait istatistiksel sonuçlar (m)

Model	N	Min (m)	Maks (m)	Ort. (m)	St.S. (m)	KOH (m)	MAO (m)
EGM2008	288	0.2525	1.6583	0.7287	0.3485	0.8077	0.7287
ITU_GGC16	288	-1.0928	1.8147	0.6422	0.6935	0.9452	0.8248
XGM2019	288	0.1372	1.1189	0.6145	0.2412	0.6601	0.6145
EIGEN-6C4	288	0.1353	1.1260	0.6119	0.2004	0.6438	0.6119
GECO	288	0.0145	1.1742	0.5808	0.2527	0.6334	0.5808

Not: Yeşil satır en iyi performansı gösteren modeli belirtmektedir. KOH = Karesel Ortalama Hata, MAO = Mutlak Ortalama Hata, St.S. = Standart Sapma

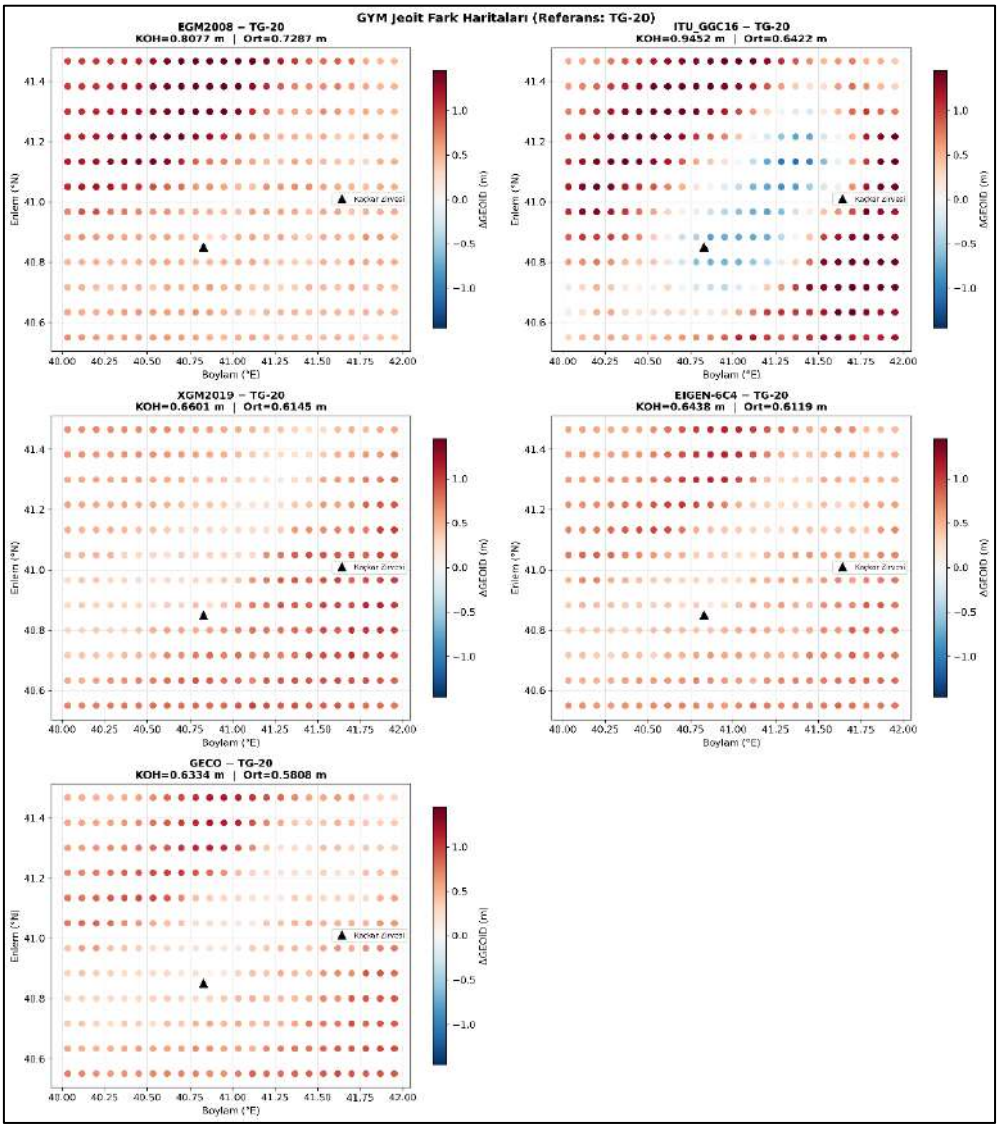
ITU_GGC16 modelinin standart sapmasının 0.6935 m ile en yüksek değerde olması bu modelin bölgede uzamsal olarak tutarsız bir davranış sergilediğine işaret etmektedir. Nitekim ITU_GGC16'nın minimum fark değeri −1.0928 m'ye kadar düşmekte, maksimum fark ise 1.8147 m'ye çıkmaktadır.

Şekil 1'te sunulan fark haritaları GYM'lerin TG-20'ye göre sapmasının coğrafi dağılımını görselleştirmektedir. Tüm modellerde ortak bir örüntü gözlemlenmektedir: bölgenin kuzeydoğusunda farklar daha küçük kalırken, güneybatıya doğru belirgin biçimde artmaktadır. Bu uzamsal örüntü topoğrafik eğimin yüksek olduğu güneybatı kesimde GYM'lerin yerel kütlesel yapıyı yeterince modelleyemediğini düşündürmektedir.

Jeoit yüksekliği farkları $\Delta N = N_{GYM} - N_{TG-20}$ şeklinde hesaplanmış ve modellerin performansı karesel ortalama hata (KOH), ortalama fark ve mutlak ortalama hata (MAO) gibi istatistiksel ölçütlerle değerlendirilmiştir (Erol vd., 2020).

GECO ve EIGEN-6C4 fark haritaları birbirine en benzer görünümü sergilemekte olup fark değerleri büyük ölçüde 0.0–0.8 m arasında kalmaktadır. EGM2008 ve XGM2019 fark haritaları

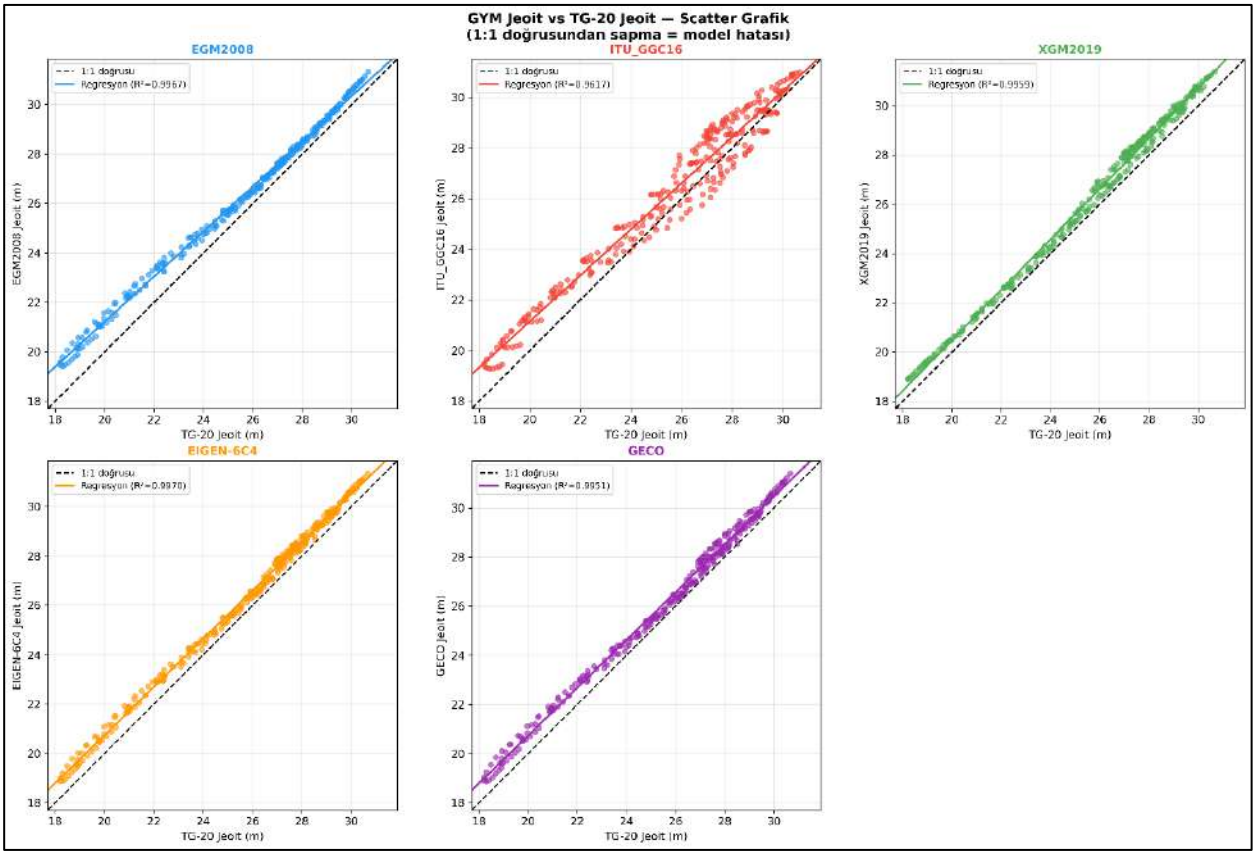
da benzer bir mekansal dağılım göstermektedir. ITU_GGC16 fark haritası ise diğer modellerden belirgin biçimde ayrışmakta ve özellikle Kaçkar zirvesinin çevresinde negatif fark bölgeleri ve Karadeniz kıyısına doğru belirgin pozitif fark bölgeleri oluşturmaktadır.



Şekil 1. DGG fark haritaları

Şekil 2'de sunulan saçılım grafikleri GYM jeoit değerleri ile TG-20 değerleri arasındaki lineer ilişkiyi ortaya koymaktadır. Tüm modeller için R^2 değerleri 0.96'nın üzerinde çıkmış olup GYM değerleri ile TG-20 arasında güçlü bir lineer ilişkinin varlığına işaret etmektedir. En yüksek R^2 değerleri EIGEN-6C4 ($R^2 = 0.9970$) ve EGM2008 ($R^2 = 0.9967$) modellerine aittir.

Bununla birlikte scatter grafiklerinde tüm modeller için 1:1 doğrusunun altında bir regresyon doğrusu gözlemlenmektedir ve bu da yukarıda tartışılan sistematik pozitif farkı doğrulamaktadır. ITU_GGC16 modeli en düşük R^2 değerini vermekte ($R^2 = 0.9617$) ve nokta dağılımı da diğer modellere kıyasla belirgin şekilde daha geniş bir bant oluşturmaktadır.



Şekil 2. GYM Saçılım Grafikleri

6. Sonuç

Bu çalışmada elde edilen bulgular GYM performansının Doğu Karadeniz dağlık bölgesinde ölçeğe ve model yapısına göre önemli ölçüde değiştiğini ortaya koymaktadır. GECO ve EIGEN-6C4 modellerinin en iyi performansı sergilemesi, GOCE uydu verilerini içeren kombine modellerin dağlık arazilerde klasik yersel veriye dayalı modellere göre daha tutarlı jeoit tahminleri ürettiğini göstermektedir. Bu bulgu Odalovic vd. (2022) ve Simav vd. (2021) tarafından rapor edilen sonuçlarla büyük ölçüde örtüşmektedir.

Türkiye'ye özgü yersel verilerle optimize edilmiş ITU_GGC16 modelinin en yüksek sapmayı vermesi ilk bakışta beklenmedik görünse de bu sonuç birkaç nedenle açıklanabilir. Birincisi ITU_GGC16'nın 280. dereceyle sınırlı harmonik genişlemesi, Kaçkar'ın ekstrem topoğrafyasının ürettiği kısa dalga boylu sinyalleri yeterince temsil edemeyebilir. İkincisi modelin türetildiği yersel gravite noktalarının Kaçkar bölgesindeki dağılımı sınırlı olabilir. Üçüncüsü TG-20 ile ITU_GGC16 arasındaki veri ve yöntem farklılıkları bölgede sistematik tutarsızlıklara yol açmış olabilir.

Bu çalışmada elde edilen bulgular, GOCE uydu verisini içeren kombine modellerin (GECO, EIGEN-6C4) dağlık bölgelerde daha yüksek doğruluk sağladığını göstermektedir. Benzer sonuçlar, farklı bölgelerde yapılan çalışmalarda da rapor edilmiştir (Erol vd., 2020; Odalovic vd., 2022).

Bununla birlikte tüm modellerin TG-20'ye göre sistematik pozitif fark göstermesi, global modellerin uzun dalga boylu bileşenlerinden kaynaklanan sistematik etkileri yansıtmaktadır (Pavlis vd., 2012; Förste vd., 2014).

Tüm modellerin TG-20'ye göre pozitif sistematik fark göstermesi önemli bir bulgudur. Bu sistematik sapma, GYM'lerin küresel ortalamalamadan kaynaklanan uzun dalga boylu hatalarını ya da TG-20 ile GYM'ler arasındaki referans sistemi farklılıklarını yansıtıyor olabilir. Söz konusu sistematik farkın giderilmesi için basit bir sabit düzeltme veya konikoid uyumu gibi yerel dönüşüm yöntemlerinin uygulanması pratik mühendislik uygulamalarında GYM performansını önemli ölçüde iyileştirme potansiyeli taşımaktadır.

Erol vd. (2020), Türkiye'de GECO tabanlı modellerin EGM2008'e kıyasla %15 iyileşme sağladığını raporlamıştır. Mevcut çalışmada GECO ve EIGEN-6C4'ün EGM2008'den yaklaşık %22 daha düşük KOH sergilemesi bu bulguyla uyumludur. Yıldız vd. (2021) tarafından geliştirilen TG-20'nin Kaçkar bölgesi doğrulama noktalarında 3–6 cm standart sapma verdiği göz önüne alındığında GYM'lerin 0.63–0.95 m düzeyindeki KOH değerleri TG-20'nin yersel veri üstünlüğünü açıkça ortaya koymaktadır.

Kaçkar Dağları bölgesinde (40.5°N–41.5°N, 40.0°E–42.0°E) beş farklı global yerpotansiyel modelden hesaplanan jeoit yüksekliği değerleri TG-20 referans modeli kullanılarak bağımsız biçimde değerlendirilmiştir. Elde edilen başlıca sonuçlar aşağıda özetlenmiştir.

GECO modeli TG-20 ile en yüksek uyumu sergilemiş (KOH = 0.6334 m), bunu EIGEN-6C4 (KOH = 0.6438 m) ve XGM2019 (KOH = 0.6601 m) izlemiştir. GOCE uydu bileşeni içeren bu modellerin daha başarılı performans göstermesi uydu tabanlı gravite verilerinin dağlık bölge jeoit modellemesine katkısını teyit etmektedir.

ITU_GGC16 modeli en yüksek sapmayı göstermiştir (KOH = 0.9452 m). Bu sonuç Türkiye'ye özgü verilerle optimize edilmiş bir modelin Kaçkar bölgesinde beklenen performansı tam olarak karşılamadığını ortaya koymaktadır. Tüm modeller TG-20'ye göre pozitif sistematik fark sergilemektedir. Bu bulgu GYM'lerin Kaçkar bölgesinde jeoit yüksekliğini sistematik olarak daha yüksek tahmin ettiğine işaret etmekte ve yerel dönüşüm uygulamalarının gerekliliğini vurgulamaktadır. En iyi GYM (GECO, KOH ≈ 0.63 m) ile TG-20 (standart sapma ≈ 1.2–6.3 cm) arasındaki doğruluk farkı, dağlık alanlarda ulusal jeoit modellerinin yersel verisinin GYM'lere kıyasla tartışmasız üstünlüğünü bir kez daha ortaya koymaktadır.

Gelecek çalışmalarda bu bölgede gerçek GPS/Nivelman noktaları ile yapılacak doğrulamalar, GYM performansına ilişkin daha kesin sonuçlar sunacaktır. Kaçkar ve Ağrı gibi farklı jeomorfolojik bölgelerin karşılaştırmalı analizi de Türkiye genelinde GYM değerlendirmesine önemli katkı sağlayacaktır. Bu çalışmanın özgün katkısı; Doğu Karadeniz'in ekstrem topoğrafik yapısına sahip Kaçkar Dağları bölgesinde TG-20 referanslı bağımsız GYM değerlendirmesinin ilk kez sistematik olarak gerçekleştirilmiş olmasıdır.

Kaynaklar

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APPLICATIONS OF SENTIMENT ANALYSIS IN CUSTOMER EXPERIENCE MANAGEMENT IN BUSINESSES

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Abstract

In the digital transformation era, customer experience management forms the foundation of competitive advantage for businesses. Social media, e-commerce platforms, and online review sites have become databases where millions of customer opinions are recorded. Sentiment analysis is the combination of natural language processing, machine learning, and deep learning technologies that transforms unstructured textual data into business intelligence. This study examines the applications of sentiment analysis in customer experience management through literature review, particularly focusing on its role in brand reputation monitoring, early crisis detection, product and service development, customer loyalty, and data-driven decision-making processes. Dictionary-based, machine learning-based, and deep learning-based approaches are compared, and the strengths and weaknesses of each method are explained. The study addresses how sentiment analysis serves as a strategic tool for businesses, how challenges such as irony, context dependence, and multilingual texts can be overcome, and presents managerial implications for creating sustainable competitive advantage.

Keywords: Sentiment analysis, customer experience, natural language processing

İŞLETMELERDE MÜŞTERİ DENEYİMİ YÖNETİMİNDE DUYGU ANALİZİ UYGULAMALARI

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Özet

Dijital dönüşüm çağında, işletmelerin müşteri deneyimi yönetimi rekabetçi avantajın temelini oluşturmaktadır. Sosyal medya, e-ticaret platformları ve çevrimiçi değerlendirme siteleri, milyonlarca müşteri görüşünün kaydedildiği veri tabanları haline gelmiştir. Duygu analizi (sentiment analysis), sözü edilen yapılandırılmamış metinsel verileri işletmesel bilgiye dönüştüren, doğal dil işleme, makine öğrenmesi ve derin öğrenme teknolojilerinin birleşiminden oluşmaktadır. Söz konusu çalışma, duygu analizinin müşteri deneyimi yönetimindeki uygulamalarını, özellikle marka itibarı izleme, erken kriz tespiti, ürün ve hizmet geliştirme, müşteri sadakati ve veri temelli karar alma süreçlerindeki rolünü literatür temelli olarak incelemektedir. Sözlük tabanlı, makine öğrenmesi tabanlı ve derin öğrenme tabanlı yaklaşımlar karşılaştırılmış, her yöntemin güçlü ve zayıf yönleri açıklanmıştır. Çalışma, işletmeler için duygu analizinin nasıl bir stratejik araç olduğunu, kinaye, bağlam bağımlılığı ve çok dilli metinler gibi zorlukların nasıl aşılacağını ele almakta, sürdürülebilir rekabet avantajı oluşturma açısından yönetsel çıkarımlar sunmaktadır.

Anahtar Kelimeler: Duygu analizi, müşteri deneyimi, doğal dil işleme

1.Giriş

Dijital teknolojinin hızlı gelişimi, müşteri-işletme etkileşiminin doğasını kökünden dönüştürmektedir. İnternet ve sosyal medya platformlarının yaygınlaşmasıyla birlikte, müşteriler ürün ve hizmetler hakkındaki görüşlerini, deneyimlerini ve memnuniyet düzeylerini çevrimiçi ortamlarda açıkça paylaşmaktadır. TripAdvisor, Booking.com, Amazon, Yelp gibi çevrimiçi değerlendirme siteleri ve Twitter, Facebook, Instagram gibi sosyal medya platformları, küresel anlamda müşteri tarafından oluşturulan içeriğin (user-generated content) kütüphanesine dönüşmüştür. Yılmaz ve Balcıoğlu (2025), sözü edilen ortamlarda müşteri duygu zekasının, işletmelerin stratejik kararlarını almada kritik bir rol oynadığını göstermektedir.

Müşteri deneyimi yönetimi, günümüzün işletme stratejisinin merkezinde yer almaktadır. Olumlu müşteri deneyimi, marka sadakati oluşturmakta, işletmelerin uzun dönem karlılığını ve pazardaki konumunu güçlendirmektedir. Ek olarak, milyonlarca müşteri değerlendirmesini insan eliyle analiz etmek uygulama aşamasında oldukça güç bir iş olarak karşımıza çıkmaktadır. Sözü edilen noktada duygu analizi, yapılandırılmamış metin verilerini sistematik bir şekilde işleyerek, işletmelere müşteri görüşlerinin genel eğilimi, müşterilerin memnuniyetsizlik alanları ve beklentileri hakkında gerçek zamanlı içgörüler sağlamaktadır.

Duygu analizi, doğal dil işleme (NLP), makine öğrenmesi (ML) ve derin öğrenme (DL) teknolojilerinin kesişim noktasında yer alan ve bir metindeki duyguları, görüşleri ve tutumları otomatik olarak tanımlayıp sınıflandıran bir yöntemdir. Malik ve Bilal (2024), çevrimiçi müşteri değerlendirmelerinin analizinde kullanılan NLP yöntemlerini kapsamlı biçimde ele alarak söz konusu alandaki çeşitliliği ve etkinliği ortaya koymaktadır. Söz konusu teknoloji, ham müşteri geri bildirimini işletme stratejilerine dönüştüren kritik bir köprü işlevi görmektedir.

Müşteri deneyimi yönetiminde duygu analizinin uygulanması, işletmelere birçok stratejik avantaj sunmaktadır. Marka itibarı izleme açısından işletmeler, müşteri görüşlerini gerçek zamanlı olarak takip

ederek olumsuz duyarlılığı erken aşamada tespit edebilmektedir. Ek olarak, müşteri sadakatini ve sürekliliğini güçlendirmeye yönelik stratejiler geliştirilebilmekte; ürün ve hizmet geliştirme süreçlerinde ise müşteri ihtiyaçları daha doğru biçimde tanımlanabilmektedir. Kriz durumlarında hızlı ve etkili bir iletişim kurma kapasitesi de söz konusu teknolojinin önemli kazanımları arasında yer almaktadır. Tüm sözü edilen işlevlerin bütünleşik etkisiyle duygu analizi, veri temelli karar alma süreçlerini destekleyerek işletmelerin rekabetçi avantajını pekiştirmektedir.

Duygu analizi, görünürde basit bir teknik izlenimi verse de ironi, kinaye, bağlam bağımlılığı, çok dilli metinler ve kültürel farklılıklar gibi pek çok güçlüğü bünyesinde barındırmaktadır. Wakchaure (2025), BERT, LSTM ve CNN gibi derin öğrenme modellerinin söz konusu zorlukları aşmada geleneksel makine öğrenmesi yöntemlerinden daha etkili olduğunu ortaya koymaktadır. Alam, Hossain Mrida ve Rahman (2025) ise 91 hakemli makalenin sistematik incelemesine dayanan çalışmalarında duygu analizinin tarihsel gelişimini, kullanılan yöntemleri, mevcut zorlukları ve gelecekteki araştırma alanlarını geniş bir perspektiften ele almaktadır.

Çalışmanın temel amacı, duygu analizinin müşteri deneyimi yönetimindeki rolünü, uygulamalarını ve potansiyelini akademik bir çerçevede sistematik olarak incelemektir. Çalışma, literatüre dayalı bir değerlendirme yöntemi izleyerek, duygu analizinin farklı yaklaşımlarını, müşteri deneyimi yönetimindeki çeşitli uygulama alanlarını ve söz konusu uygulamaların etkinliğini tartışmaktadır. Çalışmanın kapsamı, giriş, araştırma ve bulgular, sonuç bölümlerinden oluşmaktadır.

2.Literatür Temelli Bulgular Ve Uygulama Alanları

2.1. Duygu Analizinin Kavramsal Temelleri ve İşletme Yönetimine Entegrasyonu

Duygu analizi, bir metin parçasında ifade edilen subjektif bilgilerin, duygusal yüklenimin ve tutumların otomatik olarak tespit edilmesi ve sınıflandırılması işlemini ifade etmektedir. Geleneksel olarak duygu analizi, pozitif, negatif ve nötr duygular olmak üzere üç ana kategoriye ayrılmaktadır.

Ancak günümüzün daha gelişkin duygu analizi uygulamaları, sevinç, üzüntü, kızgınlık, şaşkınlık gibi detaylı duygu kategorilendirmesine de olanak sağlamaktadır.

Yılmaz ve Balcıoğlu (2025), bir otel zincirinin TripAdvisor üzerindeki 20,491 değerlendirmesini inceleyerek, duygu analizinin müşteri memnuniyetinin tarafsız bir ölçüsü olduğunu göstermektedir. Çalışmada, genel duygu dağılımı %86,4 pozitif, %7,8 nötr ve %5,8 negatif olarak tespit edilmiştir. Yalnız sayısal derecelendirmelerle (1-5 yıldız) karşılaştırıldığında, metin tabanlı duygu analizi, müşteri memnuniyetinin daha detaylı ve nüanslı bir resmini ortaya koymaktadır.

Umezurike vd. (2025b), çok platformlu duygu analizinin, sosyal medya, e-ticaret ve saha değerlendirmelerini birleştirerek, müşteri geri bildirimi yönetiminde %30 oranında müşteri memnuniyeti iyileştirmesi ve %25 müşteri alıkoyma artışı sağlayabileceğini belirtmektedir. Sözü edilen bulgu, duygu analizinin işletmeler için sadece bir analitik araç değil, stratejik bir müşteri ilişkileri yönetimi aracı olduğunu göstermektedir.

Müşteri deneyimi yönetiminde duygu analizinin entegrasyonu, işletmelerin müşteri yolculuğunun her noktasında müşteri görüşlerini anlayabilmesine olanak tanımaktadır. Manasa vd.(2025), Plutchik'in Duygu Çarkı modelini kullanarak, müşteri deneyimlerindeki temel duyguları (sevinç, güven, korku, hayal kırıklığı, üzüntü) tanımlamıştır. Sözü edilen duygu-temelli yaklaşım, işletmelerin müşteri memnuniyetini sadece istatistiksel metriklerle değil, müşterinin yaşadığı duygusal deneyimle de ölçebilmesini sağlamaktadır.

2.2. Duygu Analizi Yöntemlerinin Karşılaştırması: Sözlük Tabanlı, Makine Öğrenmesi ve Derin Öğrenme Yaklaşımları

Duygu analizinde kullanılan ana yöntemler, teknolojik gelişime paralel olarak evrim geçirmiştir. Malik ve Bilal (2024), 154 akademik çalışmanın incelemesi sonucu, duygu analizi uygulamalarında kullanılan yöntemleri tarihsel olarak kategorize etmektedir.

Sözlük tabanlı yaklaşımlar, önceden derlenmiş duygu sözlükleri (sentiment lexicons) aracılığıyla metindeki her kelimeye bir duygu puanı atamaktadır. Sözcük tabalı yöntemlerde "müthiş" gibi kelimeler pozitif, "kötü" gibi kelimeler ise negatif duygu taşıyıcısı olarak tanımlanmaktadır. Söz konusu yaklaşımın temel avantajları arasında açıklanabilir olması, hızlı işlem yapabilmesi ve az miktarda eğitim verisi gerektirmesi sayılabilir. Bununla birlikte, spesifik etki alanlarında (domain) yetersiz kalması, ironi ve sarcasm'ı algılayamaması ile yeni kelimelere uyum sağlayamaması söz konusu yöntemin başlıca kısıtlılıkları olarak öne çıkmaktadır.

Makine öğrenmesi tabanlı yaklaşımlar, Naive Bayes, Destek Vektör Makineleri (Support Vector Machines,SVM), Lojistik Regresyon, Rastgele Orman ve Gradyan Artırma gibi algoritmalar aracılığıyla eğitim veri setinden öğrenerek duygu kategorilerini tahmin etmektedir. Sözlük tabanlı yöntemlerle kıyaslandığında daha esnek ve uyarlanabilir olan söz konusu yaklaşımlar, yüksek kalitede eğitim verisi gerektirmekte ve neden-sonuç ilişkilerinin açıklanmasını güçleştirmektedir.

Derin öğrenme tabanlı yaklaşımlar, Evrişimli Sinir Ağları (Convolutional Neural Networks, CNN), Uzun Kısa Süreli Bellek (Long Short-Term Memory, LSTM), Çift Yönlü LSTM (Bidirectional LSTM, BiLSTM) ve özellikle dönüştürücü tabanlı modeller (BERT, RoBERTa, DistilBERT) gibi yapay sinir ağlarını kapsayarak metindeki bağlamsal bilgiyi ve uzun vadeli bağımlılıkları daha iyi algılayabilmektedir. Wakchaure (2025), söz konusu modellerin özelliklerini karşılaştırmalı olarak ele almaktadır. Çalışmaya göre BERT modeli, %92,7 doğruluk oranıyla Twitter, Facebook ve Reddit gibi sosyal medya veri setlerinde en yüksek performansı sergilemekte; güçlü bağlamsal anlayışı sayesinde

kinayeyi daha başarılı biçimde algılamakla birlikte eğitim süresi diğer modellere kıyasla daha uzun olmaktadır. CNN modeli, kısa metinlerdeki yerel özellikleri etkin biçimde işlemesi ve düşük GPU gereksinimleriyle öne çıkmakta; ancak uzun metinlerdeki bağlamsal ilişkileri yakalamada yetersiz kalabilmektedir. LSTM ve BiLSTM modelleri ise ardışık verilerdeki bağımlılıkları başarıyla modelleyebildiğinden zaman serisi duygu verileri ve müşteri etkileşimlerinin analizinde etkili bir tercih olmaktadır.

Alam, Hossain Mrida ve Rahman (2025), 91 makalenin sistematik incelemesi sonucu, dönüştürücü tabanlı modellerin (özellikle BERT ve türevleri) geleneksel makine öğrenmesi yöntemlerine kıyasla duygu sınıflandırmasında %15-25 oranında daha yüksek doğruluk sunduğunu göstermektedir. Ancak, ilgili modellerin hesaplama maliyeti ve veri gereksinimleri daha yüksektir.

2.3.Müşteri Deneyimi Yönetiminde Duygu Analizinin Uygulama Alanları

Marka İtibarı İzleme ve Gerçek Zamanlı İzlenebilirlik

Marka itibarı, işletmelerin en değerli malvarlığıdır. Dijital platformların yaygınlaşmasıyla birlikte sözü edilen itibarın oluşumu ve zedelenmesi artık anlık bir süreç haline gelmiş; söz konusu durum gerçek zamanlı izleme sistemlerini işletme yönetiminin vazgeçilmez bir bileşeni kılmaktadır. Rust vd. (2021), Twitter'dan çekilen veriler kullanılarak dünyanın en büyük 100 markasının haftalık, aylık ve üç aylık duygu takibini yapan bir sistem geliştirmiştir. Söz konusu sistemde müşteri görüşleri, değer-marka-ilişki çerçevesi temel alınarak marka itibarının gerçek zamanlı izlenmesini mümkün hale getirmektedir. Çalışmada duygu analizi sonuçlarının markaların finansal performansıyla ilişkili olduğu bulunmakta; sosyal medyada negatif duygu artışının 2-3 ay sonra işletme performansında düşüşle bağlantılı olduğu tespit edilmektedir.

Albladi, Islam ve Seals (2025), Twitter verilerinin NLP modelleriyle analizini kapsamlı biçimde ele alarak sosyal medya duygu analizinin marka izleme süreçlerindeki rolünü tartışmaktadır. Çalışma, dönüştürücü tabanlı modellerin geleneksel yöntemlere kıyasla gerçek zamanlı duygu tespitinde belirgin biçimde daha başarılı olduğunu ortaya koymaktadır. Sözü edilen bulgu, marka itibarı izleme sistemlerinin teknolojik altyapısının sürekli güncellenmesi gerektiğine işaret etmektedir. Benzer doğrultuda Gupta ve diğerleri (2024), Twitter verisi üzerinde LSTM tabanlı gerçek zamanlı duygu analizi gerçekleştirerek sosyal medya izleme ve kullanıcı etkileşim örüntülerinin anlık olarak takip edilebildiğini göstermektedir.

Mannaru (2025), yapay zeka destekli duygu analizinin gerçek zamanlı marka izlemedeki potansiyelini ele alarak sözü edilen sistemlerin işletmelere sağladığı rekabetçi avantajı incelemektedir. Çalışmada, yapay zeka destekli izleme sistemlerinin yalnızca negatif duyarlılığı tespit etmekle kalmayıp aynı zamanda olumlu müşteri görüşlerini de anlık olarak işleyerek marka güçlendirme stratejilerine katkı sağladığı vurgulanmaktadır. Mishra vd.(2024) ise otomotiv sektöründe marka itibarı yönetimi üzerine gerçekleştirdikleri çalışmada duygu analizinin sektörel uyarlamalar gerektirdiğini; genel amaçlı modellerin alana özgü terimler ve müşteri beklentilerini tam olarak karşılayamadığını göstermektedir.

Umezurike vd. (2025a), kriz dönemlerinde marka güveninin izlenmesinde dönüştürücü tabanlı ileri duygu analizi modellerinin önemini vurgulamaktadır. Çalışma, bir ürün hatası nedeniyle kriz yaşayan bir markanın sosyal medyada başlayan negatif duyarlılığının duygu analizi ile 12-24 saat içinde tespit edilmesinin, işletmeye kriz iletişimini önceden hazırlamada önemli bir avantaj sağladığını göstermektedir. Shaffira, Setianti ve Warta (2025) ise Brand24 platformu aracılığıyla gerçekleştirdikleri sosyal medya izleme çalışmasında marka algısının farklı platformlarda nasıl şekillendiğini analiz ederek çok platformlu izlemenin tek kanal takibine kıyasla çok daha kapsamlı ve güvenilir sonuçlar ürettiğini ortaya koymaktadır. Roshinta vd. (2024) ise gerçek zamanlı ürün boykot duygu analizinde farklı sınıflandırma algoritmalarını karşılaştırarak kriz dönemlerinde en hızlı ve doğru sonucu veren modelleri belirleyerek; söz konusu bulguların marka itibarı kriz yönetiminde algoritmik tercihler açısından yol gösterici nitelik taşıdığını vurgulamaktadır.

Erken Kriz Tespiti ve Hızlı Müşteri İletişimi

Dijital çağda negatif bir olay veya haberle ilgili sosyal medyadaki paylaşımlar dakikalar içinde milyonlara ulaşabilmektedir. Söz konusu durum, işletmelerin kriz yönetimi süreçlerini köklü biçimde dönüştürmekte; geleneksel reaktif yaklaşımların yerini proaktif, veri temelli izleme sistemleri almaktadır. Duygu analizi, işletmelerin bahsedilen krizleri erken aşamada tespit etmelerine ve hızlı yanıt vermelerine olanak tanıyan kritik bir teknoloji olarak öne çıkmaktadır. Zeng (2026), hibrit LSTM ve Yalıtım Ormanı (Isolation Forest) modelini birleştirerek geliştirdiği sistem aracılığıyla halkla ilişkiler krizlerine ilişkin sinyallerin gerçek zamanlı olarak tespit edilebildiğini göstermektedir. Sözü edilen yaklaşımda LSTM modeli sosyal medya metinlerindeki duygu örüntülerini zamansal olarak modellerken, Isolation Forest algoritması anormal duygu yoğunlaşmalarını anomali olarak işaretlemektedir. Söz konusu hibrit yapı, tek bir modele kıyasla kriz sinyallerini çok daha erken ve doğru biçimde yakalayabilmektedir. Benzer biçimde Ma ve Wang (2025), çok kaynaklı veri füzyonu ve duygu analizi temelli kamuoyu izleme ile erken uyarı sisteminin kriz iletişiminde kurumsal tepki süresini önemli ölçüde kısalttığını ortaya koymaktadır. Çalışmada sosyal medya, haber siteleri ve çevrimiçi forumlardan eş zamanlı olarak toplanan veriler birleştirilerek kamuoyu duyarlılığındaki ani değişimlerin gerçek zamanlı olarak izlenebildiği gösterilmektedir. Kriz yönetiminde duygu analizinin etkinliği, gerçek vaka çalışmalarıyla da desteklenmektedir. Xiong (2025), 2025 yılında yaşanan Haidilao olayını ele alarak duygu analizinin bir marka krizinin sosyal medyada nasıl yayıldığını ve yönetildiğini izlemede etkin bir araç olduğunu ortaya koymaktadır. Çalışmada kriz öncesi, kriz anı ve kriz sonrası dönemlerdeki duygu dağılımları karşılaştırılmış; olumsuz duyarlılığın zirveye ulaşma hızı ile işletmenin müdahale süresi arasındaki ilişki analiz edilmiştir. Benzer bir bağlamda Su (2025), aynı olayı ESG (çevresel, sosyal ve kurumsal yönetim) perspektifinden inceleyerek duygu analizinin yatırım riski erken uyarı sistemleriyle nasıl entegre edilebileceğini göstererek marka krizlerinin finansal yansımalarının duygu verileri aracılığıyla öngörülebileceğini ortaya koymaktadır. Islam, Chowdhury ve Pal (2025), doğal dil işleme ve makine öğrenmesi yöntemlerini kullanarak kriz iletişiminde kurumsal yanıtların ve paydaş etkileşiminin kapsamlı bir analizini gerçekleştirektedir. Çalışma, zamanında ve duygu odaklı iletişim

stratejilerinin kriz süreçlerinde marka güvenini korumada belirleyici bir rol oynadığını vurgulamaktadır. Çalışmaya göre, kriz anında işletmenin sosyal medyada sergilediği iletişim tonunun müşteri duyarlılığı üzerindeki etkisi, geleneksel basın açıklamalarına kıyasla çok daha hızlı ve ölçülebilir biçimde gözlemlenebilmektedir. Turki (2025) ise çok alanlı sosyal medya metin analizi için geliştirdiği otomatik çerçevede Word2Vec özellikleri ve çok katmanlı algılayıcı (multilayer perceptron) modelini bir arada kullanarak işletmelerin farklı platformlardaki duygu örüntülerini bütünleşik bir strateji perspektifinden değerlendirebildiğini göstermektedir. Tüm söz konusu bulgular bir arada değerlendirildiğinde, duygu analizinin salt bir izleme aracı olmanın ötesinde, kriz iletişimi, marka yönetimi ve rekabet stratejisi açısından bütünleşik bir erken uyarı ekosistemi işlevi gördüğü anlaşılmaktadır.

Ürün ve Hizmet Geliştirme

Duygu analizi, ürün ve hizmet geliştirme süreçlerinde müşteri sesini sistematik biçimde işletme stratejisine dönüştüren güçlü bir araç olarak öne çıkmaktadır. Geleneksel pazar araştırması yöntemlerinin zaman ve maliyet kısıtlarını aşan söz konusu yaklaşım, müşteri geri bildirimlerini gerçek zamanlı ve ölçeklenebilir biçimde işleyerek ürün geliştirme döngüsünü önemli ölçüde hızlandırmaktadır. Lee, Chung ve Park (2024), müşteri değerlendirmelerinin duygu analizi yoluyla ürün geliştirme sürecinde müşteri davranışlarının gözlemlenmesinin geleneksel yöntemlere kıyasla dört kat daha hızlı sonuç ürettiğini göstermektedir. Çalışmada müşteri satın alma deneyimi haritalama yöntemiyle davranış merkezli müşteri sesi analizi gerçekleştirilmekte; sözü edilen yaklaşım sayesinde ürün tasarımcılarının müşterinin hangi aşamalarda sorun yaşadığını, hangi özellikleri beklediğini ve hangi alternatifleri karşılaştırdığını ayrıntılı biçimde anlayabildiği gösterilmektedir.

Sanjaya, Astanti ve Ai (2025), yeni ürün geliştirme süreçlerinde duygu analizinin metin, ses, görsel ve çok modlu veriler üzerindeki uygulamalarını kapsamlı biçimde ele almaktadır. Çalışma, duygu analizinin yalnızca metin tabanlı değerlendirmelerle sınırlı kalmayıp çok katmanlı veri kaynaklarını

bütünleştirerek ürün geliştirme kararlarını daha sağlam bir temele oturtabildiğini göstermektedir. Sözü edilen bulgu, duygu analizinin ürün geliştirmedeki kullanım alanının giderek genişlediğine ve çok modlu yaklaşımların geleceğin temel yöntemi olma yolunda ilerlediğine işaret etmektedir. Simanullang ve The (2024) ise doğal dil işleme teknolojisinin yeni ürün geliştirme sürecinin konsept tasarımı, teknik tasarım ve gereksinim analizi gibi çeşitli aşamalarında etkin biçimde kullanılabildiğini göstermekte; duygu analizinin müşteri geri bildirimini işletme teknik gereksinimlerine dönüştürmede kritik bir köprü işlevi gördüğünü vurgulamaktadır.

Müşteri görüşlerinin ürün geliştirme sürecine entegrasyonu, Kalite İşlev Yayılımı (Quality Function Deployment, QFD) ve Kano modeli gibi geleneksel yöntemlerle de birleştirilerek güçlendirilebilmektedir. Muhassab (2025), çevrimiçi değerlendirmelerin duygu analizi yoluyla işlenmesini QFD ve Kano modeli ile bütünleştiren bir çerçeve geliştirerek; sözü edilen entegre yaklaşımın hem ürün kalitesini hem de müşteri memnuniyetini iyileştirmede geleneksel yöntemlere kıyasla daha etkili sonuçlar ürettiğini ortaya koymaktadır. Akter vd. (2024) ise kullanıcı yorumlarının duygu analizini e-ticaret uygulama öneri sistemleriyle birleştirerek soğuk başlangıç (cold-start) sorununa yenilikçi bir çözüm sunmakta; duygu temelli öneri sistemlerinin müşteri deneyimini iyileştirmedeki etkinliğini karşılaştırmalı analizle ortaya koymaktadır.

Tüm sözü edilen bulgular bir arada değerlendirildiğinde, duygu analizinin ürün ve hizmet geliştirme süreçlerinde salt bir geri bildirim toplama aracı olmanın ötesine geçerek stratejik bir tasarım ve karar destek aracına dönüştüğü görülmektedir. Müşteri sesini gerçek zamanlı ve çok boyutlu biçimde işleme kapasitesi, işletmelerin pazar değişimlerine daha hızlı uyum sağlamasına ve rakiplerine karşı ürün geliştirme sürecinde kalıcı bir rekabetçi avantaj elde etmesine imkan tanımaktadır.

Müşteri Sadakati ve Elde Tutma Stratejileri

Müşteri sadakati ve elde tutma, işletmelerin uzun vadeli sürdürülebilirliği açısından kritik öneme sahip olmakla birlikte, söz konusu alanda duygu analizinin rolü giderek daha belirgin hale gelmektedir. Geleneksel müşteri kaybı tahmin yöntemleri, demografik ve işlemsel verilere dayanırken; duygu analizi, müşterinin duygusal durumunu ve memnuniyet düzeyini doğrudan ölçerek ilgili süreçlere yeni bir boyut katmaktadır.

Anitha, Sherly ve Tseng (2025), RFM (Recency, Frequency, Monetary) yöntemiyle elde edilen özellikler ve duygu analizi verilerini GraphSAGE modeli aracılığıyla birleştirerek müşteri kaybı tahmininde önemli bir doğruluk artışı sağlamaktadır. Sözü edilen entegre yaklaşım, yalnızca işlemsel geçmişe dayanan modellerle karşılaştırıldığında müşteri ayrılma riskinin çok daha erken ve isabetli biçimde tespit edilebildiğini ortaya koymaktadır. Benzer biçimde Awate, Kumar ve Sharma (2025), derin öğrenme temelli dinamik segmentasyon ve duygu tahmini yöntemini bir arada kullanarak çevrimiçi platformlarda müşteri elde tutma oranlarını iyileştirmeye yönelik bir çerçeve geliştirmektedir. Çalışmada duygu tahmininin müşteri segmentasyonuyla eş zamanlı yürütülmesinin, bireysel müşteri davranışlarına yönelik daha hassas ve kişiselleştirilmiş müdahale stratejileri geliştirilmesine olanak tanıdığı gösterilmektedir.

Lappeman, Franco, Warner ve Sierra-Rubia (2022), sosyal medya duygu analizinin müşteri kaybı nedenlerini anlamlandırmadaki rolünü inceleyerek; müşterilerin ayrılma kararı vermeden önce sosyal medyada sergiledikleri duygu örüntülerinin söz konusu kararın önemli bir öngörücüsü olduğunu ortaya koymaktadır. Çalışma, sosyal medya duyarlılığının geleneksel anket temelli memnuniyet ölçümlerine kıyasla müşteri kaybını çok daha erken sinyalleyebildiğini göstermesi bakımından literatüre özgün bir katkı sunmaktadır. Gao, Li ve Ma (2025) ise derin öğrenme algoritmaları aracılığıyla e-ticaret platformu kullanıcı yorumları üzerinde ikili duygu analizi gerçekleştirerek ve elde edilen bulguları duygu odaklı pazarlama stratejilerinin optimizasyonunda kullanmaktadır. Çalışmada, duygu analizi sonuçlarına

dayalı olarak kurgulanan kişiselleştirilmiş pazarlama iletişiminin müşteri bağlılığını ve tekrar satın alma eğilimini olumlu yönde etkilediği gösterilmektedir.

Müşteri elde tutma stratejilerinde duygu analizinin bir diğer uygulama alanı, yapay zeka destekli müşteri etkileşim sistemleridir. Kumar (2025), duygu raporlama kapasitesine sahip duygu farkındalıklı sohbet robotlarının müşteri elde tutma üzerindeki etkisini incelemiş; sözü edilen sistemlerin müşteri şikayetlerine duygusal bağlam çerçevesinde yanıt vererek müşteri memnuniyetini artırdığını ortaya koymaktadır. Liu-Thompkins vd. (2022), pazarlama etkileşimlerinde yapay empatinin müşteri deneyimi üzerindeki rolünü ele alarak insan-yapay zeka arasındaki duygusal boşluğun kapatılmasının müşteri sadakati açısından belirleyici bir etken olduğunu vurgulamaktadır. Zhong (2025) ise uzamsal-zamansal özellikler ve çok modlu duygu tanımayı bütünleştiren bir model geliştirerek e-ticaret tüketici davranışlarının tahmininde duygu verisinin belirleyici rolünü ortaya koymaktadır.

Tüm sözü edilen bulgular bir arada değerlendirildiğinde, duygu analizinin müşteri sadakati ve elde tutma stratejilerinde yalnızca bir ölçüm aracı olarak değil, proaktif müdahale mekanizmaları geliştiren bütünleşik bir karar destek sistemi olarak konumlandırılması gerektiği anlaşılmaktadır.

3. Duygu Analizi Uygulamalarında Karşılaşılan Zorluklar ve Çözüm Yolları

Duygu analizi, güçlü bir teknoloji olmasına karşın çeşitli yapısal ve kültürel güçlükleri barındırmaktadır. Sözü edilen güçlüklerin başında kinaye gelmektedir. Bir metin kelime düzeyinde olumlu bir anlam taşısa bile kinaye yoluyla tam tersi bir duyguyu ifade edebilmektedir. "Bu hizmet harika! Üç saat bekledim" gibi bir yorum, duygu analizi algoritması tarafından pozitif olarak sınıflandırılabilirken aslında olumsuz bir deneyimi yansıtmaktadır. Alam, Hossain Mrida ve Rahman (2025), 91 makalenin sistematik incelemesinde dönüştürücü modellerinin kinaye tespitinde geleneksel yöntemlere kıyasla %10-15 oranında daha yüksek performans sergilediğini ortaya koymaktadır.

Bağlam bağımlılığı da duygu analizinde önemli bir güçlük kaynağı oluşturmaktadır. Aynı kelime veya ifade, farklı bağlamlarda birbirinden farklı duygusal yükler taşıyabilmektedir. "Fiyat uygun"

ifadesi bütçe odaklı bir ürün kategorisinde olumlu bir nitelik olarak algılanırken, lüks segment değerlendirmelerinde düşük kalitenin göstergesi olarak olumsuz biçimde yorumlanabilmektedir.

Çok dilli metinler de duygu analizinin önündeki yapısal engellerden birini oluşturmaktadır. Türkçe, Arapça ve Bengalce gibi dillerde İngilizceye kıyasla yeterli duygu sözlüğü ve eğitim verisi bulunmamaktadır. Khan, Amjad, Ashraf ve Chang (2022), Urduca için 9.312 manuel olarak etiketlenmiş müşteri değerlendirmesi kullanarak çok dilli BERT modelini (mBERT) ince ayar yöntemiyle geliştirerek %81,49 F1 skoru elde etmiştir. Söz konusu bulgu, çok dilli dönüştürücü modellerinin kaynak kısıtlı dillerdeki uygulanabilirlik potansiyelini göstermesi bakımından önem taşımaktadır.

Alan uyarlaması da duygu analizinin etkinliğini doğrudan etkileyen bir etken olarak öne çıkmaktadır. Tıbbi, finansal veya hukuki alanlarda genel amaçlı duygu sözlükleri ve modeller yetersiz kalabilmektedir. Lee, Chung ve Park (2024), alana özgü verilerle gerçekleştirilen model eğitiminin doğruluk oranını %10-20 oranında artırabildiğini göstermektedir.

Veri kalitesi ve dengesizliği de duygu analizi modellerinin başarısını kısıtlayan önemli bir etkendir. Çevrimiçi değerlendirmelerde olumlu yorumların oranı genellikle %70-80 düzeyinde seyretmekte; sözü edilen durum modellerin azınlık sınıfı olan olumsuz yorumları öğrenmesini güçleştirmektedir. Malik ve Bilal (2024), ilgili dengesizliğin giderilmesinde SMOTE (Synthetic Minority Over-sampling Technique) ve benzer örnekleme tekniklerinin etkin biçimde kullanılabileceğini belirtmektedir. Ek olarak, sınıf ağırlıklandırma ve alt örnekleme yöntemleri de veri dengesizliğiyle başa çıkmada yaygın olarak başvurulan teknikler arasında yer almaktadır. Model değerlendirme aşamasında ise yalnızca doğruluk metriğine dayanmak yerine F1 skoru, hassasiyet ve duyarlılık gibi dengesiz veri setleri için daha bilgilendirici metriklerin kullanılması önerilmektedir.

Son olarak, etik ve mahremiyet boyutu duygu analizinin göz ardı edilemeyecek bir kısıtlılığını oluşturmaktadır. Müşteri verilerinin duygu analizi amacıyla işlenmesi, kişisel verilerin korunması mevzuatı gibi düzenlemelerle uyumlu biçimde yürütülmesini zorunlu kılmaktadır. Ek olarak, duygu analizi bulgularının müşteri manipülasyonu gibi etik dışı amaçlarla kullanılması, hem kurumsal itibar hem de toplumsal güven açısından ciddi riskler barındırmaktadır. Açıklanabilir yapay zeka (Explainable

AI, XAI) yaklaşımlarının benimsenmesi ve algoritmik şeffaflığın artırılması, duygu analizi sistemlerinin etik çerçevede işletilmesine katkı sağlayan önemli adımlar olarak değerlendirilmektedir.

4. Sonuç

Duygu analizi, dijital çağda müşteri deneyimi yönetiminin temel araçlarından biri haline gelmiştir. Çalışma, duygu analizinin kavramsal temellerini, teknolojik yaklaşımlarını, müşteri deneyimi yönetimindeki çeşitli uygulama alanlarını ve karşılaşılan güçlükleri sistematik biçimde ele almaktadır.

Çalışmanın bulguları, duygu analizinin sözlük tabanlı, makine öğrenmesi tabanlı ve derin öğrenme tabanlı olmak üzere üç ana yaklaşım çerçevesinde uygulandığını ortaya koymaktadır. Dönüştürücü tabanlı modeller (BERT, RoBERTa), geleneksel yöntemlere kıyasla daha yüksek doğruluk oranları sunmakla birlikte daha fazla hesaplama kaynağı gerektirmektedir. Uygulama alanları açısından değerlendirildiğinde, duygu analizinin marka itibarı izleme, erken kriz tespiti, ürün ve hizmet geliştirme, müşteri sadakati tahminlemesi ve veri temelli karar alma süreçlerinde stratejik bir işlev üstlendiği görülmektedir. Yılmaz ve Balcıoğlu (2025) ile Umezurike vd. (2025b) gibi çalışmalar, duygu analizinin müşteri memnuniyetinde %25-30 oranında iyileştirme sağlayabileceğini göstermektedir. Öte yandan kinaye, bağlam bağımlılığı, çok dilli metinler, alan uyarlaması, veri dengesizliği ve etik konular, duygu analizi uygulamalarında karşılaşılan başlıca güçlükler olarak öne çıkmaktadır. Sözü edilen güçlüklerin aşılması, ileri derin öğrenme tekniklerinin, alana özgü eğitim verilerinin ve sorumlu veri yönetimi yaklaşımlarının bir arada benimsenmesini gerektirmektedir.

Yönetsel açıdan değerlendirildiğinde, işletmelerin duygu analizini müşteri ilişkileri yönetimi, iş zekası ve ürün geliştirme sistemlerine bütünleşik biçimde entegre etmesi önerilmektedir. Model seçiminde büyük ölçekli işlemler için dönüştürücü modellerinin tercih edilmesi, hesaplama kaynakları kısıtlı olan durumlarda ise makine öğrenmesi modellerinin değerlendirilmesi önerilebilir. Kaliteli ve dengeli eğitim veri seti oluşturulması ile alana özgü uyarlamaların yapılması, model performansını doğrudan etkileyen kritik etkenler arasında yer almaktadır. Duygu analizinin tamamen otomatikleştirilmek yerine özellikle kritik kararlar söz konusu olduğunda insan uzmanı doğrulamasıyla desteklenmesi, daha sağlıklı sonuçlar üretilmesi bakımından değerli görünmektedir. Ek olarak müşteri

verilerinin korunması, gizlilik düzenlemelerine uyum ve duygu analizi bulgularının etik sınırlar içinde kullanılması, sürdürülebilir ve güvenilir bir uygulama çerçevesinin vazgeçilmez bileşenleri olarak değerlendirilebilir.

Gelecekteki araştırmaların Türkçe, Arapça ve diğer düşük kaynaklı dillerde duygu analizi uygulamalarının geliştirilmesine, metin, görüntü ve ses verilerini bir arada işleyen çok modlu duygu analizi yaklaşımlarına, gerçek zamanlı ve akışkan veri ortamlarında duygu analizi kullanımına, sektöre özgü model geliştirme çalışmalarına ve açıklanabilir yapay zeka ile etik boyutların derinlemesine incelenmesine yönelmesi, alanın gelişimine önemli katkılar sunabilir.

Sonuç olarak duygu analizi, işletmelerin müşteri deneyimi yönetiminde rekabetçi avantaj kazanması için giderek daha değerli bir araç haline gelmektedir. Teknoloji, etik ilkeler ve yönetim uygulamalarının bütünleşik biçimde ele alınması, duygu analizinin işletmelerin müşteri odaklılığını güçlendirerek uzun vadeli başarılarını pekiştirmesine önemli katkılar sunacaktır.

Kaynakça

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HASTANEDE YATAN ÇOCUĞUN TIBBİ İŞLEM KORKUSUNUN PSİKOSOSYAL SEMPTOMLAR ÜZERİNE ETKİSİ

THE EFFECT OF MEDICAL PROCEDURE ANXIETY ON PSYCHOSOCIAL SYMPTOMS IN A HOSPITALIZED CHILD

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ÖZET

Bu araştırma, hastaneye yatan çocuklarda tıbbi işlem korkusunun psikososyal semptomlar üzerine etkisi belirlemek amacıyla tanımlayıcı tipte gerçekleştirilmiştir.

Araştırma bir üniversite hastanesinin Pediatri Kliniği'nde yatarak tedavi gören 306 çocuk ve ebeveyni ile yürütülmüştür. Veriler; "Sosyodemografik Bilgi Formu", "Tıbbi İşlem Korku Ölçeği" ve "Hastanede Yatan Çocuklar İçin Psikososyal Semptomları Tanılama Ölçeği" kullanılarak yüz yüze anket yöntemiyle toplanmıştır. Verilerin analizinde IBM SPSS Statistics 22.0 programı kullanılmış; tanımlayıcı istatistiklerin yanı sıra Mann–Whitney U, Kruskal–Wallis ve Spearman korelasyon analizleri uygulanmıştır.

Araştırmada Tıbbi İşlem Korku Ölçeği toplam puan ortalaması 62.9±10.6 ve Psikososyal Semptom Tanılama Ölçeği puan ortalaması 24.2±6.4 olarak belirlenmiştir. Çocukların yaş ortalamasının 8.8±1.72 olduğu ve %88.6'sının akut hastalık nedeniyle hastanede yattığı saptanmıştır. Çocuklarda tıbbi işlem korkusu ile psikososyal semptomlar arasında anlamlı ve pozitif bir ilişki olduğu belirlenmiştir ($p<0.05$).

Araştırmada, çocukların psikososyal semptomlarının bazı sosyodemografik ve klinik özelliklere göre anlamlı farklılık gösterdiği belirlenmiştir. Özellikle damar yolu açılma durumu ve daha önce hastaneye yatma deneyimi, psikososyal semptomlar üzerinde belirgin etkiye sahiptir. Çocukların tıbbi işlemlere yönelik korkularının azaltılması, psikososyal semptomların önlenmesi ve tedavi sürecine uyumlarının artırılması açısından büyük önem taşımaktadır.

Anahtar kelimeler: Çocuk, Hastaneye yatma, Korku, Tıbbi işlem, Psikososyal belirtiler

ABSTRACT

This descriptive study aimed to determine the effect of fear of medical procedures on psychosocial symptoms in hospitalized children.

The study was conducted with 306 children and their parents who were hospitalized in the Pediatric Clinic of a university hospital. Data were collected using a face-to-face survey method with the "Sociodemographic Information Form," the "Medical Procedure Fear Scale," and the "Psychosocial Symptom Assessment Scale for Hospitalized Children." IBM SPSS Statistics 22.0 program was used

for data analysis; in addition to descriptive statistics, Mann–Whitney U, Kruskal–Wallis, and Spearman correlation analyses were applied.

In the study, the mean total score of the Medical Procedure Fear Scale was determined as 62.9±10.6 and the mean score of the Psychosocial Symptom Assessment Scale was 24.2±6.4. The average age of the children was found to be 8.8±1.72, and 88.6% were hospitalized due to acute illness. A significant and positive relationship was determined between fear of medical procedures and psychosocial symptoms in children ($p<0.05$).

The study determined that children's psychosocial symptoms differed significantly according to some sociodemographic and clinical characteristics. In particular, intravenous access and previous hospitalization experience had a significant effect on psychosocial symptoms. Reducing children's fear of medical procedures is of great importance in preventing psychosocial symptoms and increasing their compliance with the treatment process.

Keywords: Child, Hospitalization, Fear, Medical procedure, Psychosocial symptoms

GİRİŞ

Hastalık, hastane ortamı ve hastanede yatış her yaş grubunda bulunan çocuk için korkutucu ve rahatsız edici bir deneyimdir. Yeni ve bilinmeyen bir çevreye uyum sağlamanın yanı sıra sık sık karşılaşılan tıbbi işlemler çocuklarda korku ve kaygıya neden olabilmektedir (Üstün vd., 2014, 2021).

Çocukların hastaneye ilişkin korkularının daha çok aileden uzak kalma, iğne ve kan tahlilleri, hastanede uzun süre kalma, gürültülü cihaz ve monitörler, invaziv girişimler ve bu girişimler sırasında ağrı hissetme, muayene olma, doktor/hemşire korkusu, kontrol kaybı, ameliyat olma ve ölüm olduğu belirlenmiştir (Marasuna ve Eroğlu 2013; Üstün ve ark. 2014).

Çocuğun hastalık ve hastane ortamına uyum düzeyi çeşitli faktörlere bağlı olarak değişim göstermektedir. Bu faktörlerden bazıları çocuğun yaşı, bilişsel gelişim seviyesi, hastalığın süresi ve niteliği, geçmiş hastane ve/veya hastalık deneyimleri, hastane sürecine hazırlığı ve ailenin kültürel yapısını kapsamaktadır (Üstün ve ark, 2014). Bu doğrultuda; çocukların hastane ortamında yaşadıkları stres ve korku, hastalık ve hastane ortamına uyum sürecini uzatabilir, iyileşme sürecini geciktirebilir ve sağlık profesyoneli ile çocuk arasındaki işbirliğini azaltabilir (Çalişir vd., 2022; Kain vd., 2007; Proczkowska-Björklund vd., 2008) Yapılan bazı araştırmalara göre çocuklarda görülen tıbbi işlemlere yönelik korkuların geçmişte yaşanılan travmatik deneyimler ve/veya sosyal öğrenme ile oluşabileceği bildirilmektedir (Akkavak & Karabudak, 2019; Carman & Kyle, 2012).

Bu doğrultuda, çocukların travmatik deneyimleri ve sosyal öğrenme süreçleri göz önüne alınarak sağlık hizmetlerinin sunulması olası tıbbi işlemlere yönelik kaygı ve korkularının engellenmesinde önemli rol oynamaktadır (Akkavak & Karabudak, 2019; Maraşuna & Eroğlu, 2013).

Hastaneye yatmanın çocuğun gelişimi üzerinde biyolojik, ruhsal, sosyal, çevresel, ailesel, psikososyal ve psikoseksüel etkileri olduğundan söz edilmektedir. Çocukların hastane sürecinde çeşitli olumsuz durumlarla karşılaşması, çocuğun fiziksel sorunlarının yanı sıra psikososyal sorunları yaşamasına neden olabilmektedir. Hastalığa ve tıbbi korkuya karşı geliştirilen tepkiler, çocuğun benliğini ve bütünlüğünü korumak için ortaya çıkan bilişsel, emosyonel ve davranışsal yanıtları içermektedir (Başay et al., 2020).

Bu sorunların erken dönemde tanımlanıp tedavi edilmemesi çocukların ilerleyen yaşlarda yaşayacağı kısıtlamalara ve kalıcı psikososyal etkilere yol açabilmektedir (Carman & Kyle, 2012; Çelebi vd., 2015). Ayrıca söz konusu durumun çocuklarda, hastalık ve tedaviye daha az uyumun sağlanması, öngörülen iyileşme sürecini uzatması, morbidite ve mortalite oranlarının artmasına neden olabileceği gibi çocukların ve ailelerin yaşam kalitesini düşürürken hastane maliyetini artırabilmektedir (Arachchige Dona et al., 2025).

Yapılan çalışmalarda hastaneye yatma deneyimi yaşayan çocukların psikososyal semptomlar olarak sıklıkla korku, regresyon, üzüntü, umutsuzluk, ilgisizlik, sevgi yoksunluğu, ayrılık anksiyetesi, yalnızlık ve sosyal izolasyon, cezalandırılma düşünceleri, güçsüzlük ve yetersizlik güven eksikliği, öfke,

suçluluk, beden imajında değişiklik, somatik yakınmalar, yaşadıkları belirlenmiştir (Demetriou et. al. 2024).

İleri düzeyde psikososyal semptomlar yaşayan çocuklarda tik ve kekemelik gibi regresif davranışlar, anksiyete ve depresyon belirtileri, fobik semptomlar, konversiyon belirtileri, uyku ve beslenme bozuklukları ile ölüm korkusu görülebilmektedir. Bu durum, hastaneye yatışın ve tıbbi işlemlerin bazı çocuklar için travmatik bir deneyime dönüşebildiğini göstermektedir. Stanzel & Sierau (2021) tarafından yapılan sistematik derlemede, cerrahi girişim geçiren çocuk ve ergenlerde anksiyete, depresif belirtiler, travma sonrası stres belirtileri ile içe yönelim ve dışa yönelim davranış sorunlarının gelişebildiği bildirilmiştir.

Bu doğrultuda sağlık profesyonellerinin, hastane sürecini yaşayan çocuklarda sadece fiziksel iyilik halinin sağlanmasının yanı sıra psikososyal iyilik halinin sağlanması ve/veya sürdürülmesi için tanı ve tedavide mutlak holistik yaklaşımı ele alması gerektiği bildirilmektedir (Legg 2011). Holistik bir yaklaşımda, özellikle hemşirelerin rolü hayati öneme sahiptir. Hemşirelerin psikososyal değerlendirmeleri ve müdahaleleri, çocukların hastane deneyimlerini olumlu yönde etkileyebilir, korkularını hafifletebilir ve genel yaşam kalitelerini yükseltebilir. İngiltere'de yapılan bir çalışmada, çocuklarla ilgilenen hemşirelerin sadece güler yüzlü ve nazik tutumlarının bile çocukların psikososyal yanıtlarını hafifletebileceği belirtilmiştir (Santos vd., 2016).Bu bağlamda, hemşirelerin çocukların psikososyal bakımına yönelik kapsamlı bir eğitim alması, çocuk sağlığı hedeflerine ulaşmada etkin bir unsur olmaktadır. Özellikle primer bakım verici hemşirelerin, çocukların duygusal ve sosyal ihtiyaçlarına yanıt verebilecek kapasiteye sahip olması, güçlü terapötik ilişkiler kurabilmesi ve aileleri tedavi sürecine aktif olarak dahil edebilmesi için gerekli bilgi ve becerilere sahip olması gerekmektedir. Bu durum, çocukların psikososyal bakımı açısından, hemşirelerin rolünün sadece tıbbi uygulamalarla sınırlı olmadığını, aynı zamanda çocuğun genel iyilik hâli ve yaşam kalitesi üzerinde de etkili olduğunu vurgulamaktadır. Dolayısıyla, çocuk sağlığı ve psikososyal bakım konularında hemşirelerin geniş kapsamlı bir eğitim alması, çocukların sağlık durumlarının belirgin bir şekilde geliştirilmesinde etkili bir faktör olarak kabul edilmektedir (Başay vd., 2020; Dur vd., 2016; Santos vd., 2016; Teksöz & Ocakçi, 2014). Bu çalışmanın amacı, hastanede yatan çocukların tıbbi işlem korkusunun psikososyal semptomlar üzerindeki etkisini incelemektir.

GEREÇ VE YÖNTEM

Araştırmanın amacı ve tasarımı

Bu çalışma, hastaneye yatan çocuklarda tıbbi işlem korkusunun psikososyal semptomlar üzerine etkisi belirlemek amacıyla tanımlayıcı ve kesitsel bir çalışma olarak tasarlanmıştır.

Çalışma, Mayıs 2023 ve Aralık 2023 tarihleri arasında, bir üniversite hastanesinin Çocuk kliniğinde yatarak tedavi gören 7-12 yaş arasında çocuk ve ebeveynleriyle gerçekleştirilmiştir.

Araştırmanın Örneklemi

Araştırmanın örneklemini, Mayıs 2023–Aralık 2023 tarihleri arasında bir Üniversite hastanesinin Çocuk kliniğine yatışı yapılan 7-12 yaş aralığında olan çocuk hastalardan örneklem seçim kriterlerine uyan ve çalışmaya katılmayı kabul eden 306 çocuk ve ebeveynleri oluşturmuştur. Araştırmanın dahil edilme kriterlerinde ise, çocuğun akut veya kronik bir hastalık tanısı almış olması, çocuğun herhangi bir psikiyatrik hastalık tanısının bulunmaması ve çocuğun en az üç gün hastanede yatıyor olması dikkate alınmıştır.

Veri Toplama Araçları

Araştırmada veriler, “Tanımlayıcı Bilgi Formu”, “Tıbbi İşlem Korku Ölçeği” ve “Hastanede Yatan Çocuklar İçin Psikososyal Semptomları Tanılama Ölçeği” kullanılarak toplanmıştır.

Tanımlayıcı Bilgi Formu: Araştırma kapsamına alınan çocukların ve ebeveynlerinin yaş, cinsiyet, eğitim durumu, mesleği, kardeş sayısı gibi sosyodemografik bilgileri ile çocukların hastane deneyimlerine ilişkin bilgilerin elde edilmesine yönelik 19 sorudan oluşmuştur.

Tıbbi İşlem Korku Ölçeği: Tıbbi İşlem Korku Ölçeği (TİKÖ), çocukların tıbbi işlemler ve hastane uygulamalarına yönelik korku düzeylerini değerlendirmek amacıyla Marion Bloom ve arkadaşları tarafından 1985 yılında geliştirilmiştir. Ölçek, toplam 29 maddeden oluşmakta ve çocukların tıbbi işlemlerle ilişkili korkularını dört alt boyutta değerlendirmektedir: işlemsel, çevresel, kişisel ve kişilerarası korkular. Ölçeğin özgün formunda iç tutarlılık katsayısı (Cronbach alfa) 0,93, geçerlik katsayısı ise 0,78 olarak bildirilmiştir. Ölçeğin Türkiye'deki geçerlik ve güvenirlik çalışması Alak tarafından 1993 yılında gerçekleştirilmiştir. Bu çalışmada, 7–14 yaş grubundaki 100 sağlıklı okul çocuğu üzerinde yapılan analizlerde Split-Half Güvenirlik Ölçütü ve Spearman-Brown Tekniği kullanılmış; Spearman-Brown güvenirlik katsayısı 0,93 olarak saptanmıştır. Bu araştırmada ise ölçeğin Cronbach alfa katsayısı 0,91 olarak bulunmuştur. TİKÖ, üçlü Likert tipinde bir ölçektir. Her madde için çocuklardan "Hiç korkmam" (1 puan), "Biraz korkarım" (2 puan) ve "Çok korkarım" (3 puan) seçeneklerinden kendilerine en uygun olanı işaretlemeleri istenir. Ölçekten alınabilecek toplam puan 29 ile 87 arasında değişmektedir. Yüksek puan, çocuğun tıbbi işlemlere yönelik korku düzeyinin daha fazla olduğunu göstermektedir. Toplam puan değerlendirmesinde, 29 puan "hiç korkmayan", 30–58 puan "biraz korkan" ve 59–87 puan "çok korkan" olarak yorumlanmaktadır. Ölçeğin alt boyutlarına ilişkin puan aralıkları şu şekildedir:

- İşlemsel korkular: 9–27 puan
- Çevresel korkular: 7–21 puan
- Kişisel korkular: 4–12 puan
- Kişilerarası korkular: 9–27 puan

Hastanede Yatan Çocuklar İçin Psikososyal Semptomları Tanılama Ölçeği:

Hastanede Yatan Çocuklar İçin Psikososyal Semptomları Tanılama Ölçeği, Üstün ve Kelleci tarafından 2013 yılında geliştirilmiş ve 6–12 yaş grubundaki hastanede yatan çocukların psikososyal semptomlarını değerlendirmek amacıyla kullanılmaktadır. Ölçek, toplam 24 maddeden oluşmakta ve üçlü Likert tipinde düzenlenmiştir. Her bir madde "hiçbir zaman", "bazen" ve "sık sık" seçenekleri ile değerlendirilmektedir; bu seçenekler sırasıyla 0, 1 ve 2 puan olarak puanlanmaktadır. Ölçekten alınabilecek toplam puan 0 ile 48 arasında değişmektedir. Ölçek; Anksiyete, Umutsuzluk, İletişim Güçlüğü, Öfke ve Saldırganlık ile Regresyon olmak üzere beş alt boyuttan oluşmaktadır. Ölçeğin geliştirme çalışmasında iç tutarlılık katsayısı (Cronbach alfa) 0,90 olarak bulunmuştur. Toplam puanın yükselmesi, hastanede yatan çocuğun psikososyal sorunlarının ve semptomlarının daha fazla olduğunu göstermektedir. (Üstün ve Kelleci, 2013)

Verilerin Toplanması

Veriler, Mayıs 2023–Aralık 2023 tarihleri arasında hastanenin çocuk kliniklerinde yatan çocuk hasta ve ebeveynleri ile görüşülerek elde edilmiştir. Psikososyal semptom tanılama ölçeği en az üç gün çocuğu takip eden araştırmadan bağımsız bir hemşire tarafından uygulanmıştır. Yüzyüze görüşmeler hasta odasında, hastaneye yatışın üçüncü veya dördüncü gününde gerçekleştirilmiştir. Kişisel Bilgi Formu anneden alınan bilgiler doğrultusunda araştırmacı tarafından; yine TİKÖ çocuklar ile görüşülerek araştırmacı tarafından doldurulmuştur. Hemşire araştırmanın yapıldığı klinikte, çocuğun rutin bakım ve tedavi uygulamaları sırasında çocukları gözlemlemiştir. Hemşire, çocuğun bakımına doğrudan katılmış ve en az üç gün boyunca takip ettiği çocuk için ÇPSTÖ'yü doldurmuştur.

Verilerin Analizi

Bu araştırmada elde edilen veriler IBM SPSS Statistics Version 25 paket programı ile analiz edilmiştir. Verilerin çözümlenmesinde ölçeklerde sürekli yapıdaki verilen istatistiği yapılırken ortalama ve standart sapma, min. ve max. değerleri; kategorik değişkenleri tanımlarken frekans ve yüzde değerler

kullanılmıştır.Ölçümlerin iki bağımsız grup ortalamalarını karşılaştırmada Student's t test, ikiden fazla bağımsız gurup ortalamalarını karşılaştırmak için ise One Way ANOVA test istatistiği kullanılmışır. Ölçek Toplam puanlar arası ilişki değerlendirmede Pearson Korelasyon istatistiği kullanılmıştır.

Etik Onay

Araştırmaya başlamadan önce Etik Kurulu onayı (Karar no:02/37,Tarih:18.04.2023) ve çalışmanın gerçekleştirildiği kurumdan izin alınmıştır. Araştırmaya katılan ebeveynlerden, yazılı bilgilendirilmiş onamları alınmıştır. Katılımcıların kimlik bilgileri ve mahremiyetleri korunmuş olup, toplanan veriler yalnızca bu araştırma amacıyla kullanılmıştır.

BULGULAR

Hastanede yatan çocukların tıbbi işlem korkusunun psikososyal semptomlar üzerindeki etkisini incelemek üzere yapılan bu çalışmada aşağıdaki bulgular elde edilmiştir.

Tablo 1. Ebeveynlerin tanıtıcı özellikleri (n=306)

Değişkenler	**Ort.+SS**	**Min-Max**
Yaş ortalama (anne)	**35.1±5.6**	**24-51**
Yaş ortalama (baba)	**37.8±5.7**	**27-60**
	n	**%**
Anne eğitim durumu		
İlkokul	76	24.8
Ortaokul	53	17.3
Lise	133	43.5
Üniversite /Yüksekokul	44	14.4
Baba eğitim durumu		
İlkokul	35	11.4
Ortaokul	54	17.6
Lise	151	49.3
Üniversite /Yüksekokul	66	21.7
Aile gelir durumu		
Gelir giderden az	64	20.9
Gelir gidere eşit	179	58.5
Gelir giderden çok	63	20.6
Aile tipi		
Çekirdek aile	260	85.0
Geniş aile	46	15.0
Yaşadıkları yer		
İl	209	68.3
İlçe	72	23.5
Köy/kasaba	25	8.2

Tablo 1 incelendiğinde, annelerin yaş ortalamasının 35.1±5.6 ve babaların yaş ortalamasının 37.8±5.7 olduğu belirlenmiştir. Annelerin %43.5'inin ve babaların %49.3'ünün lise mezunu olduğu, %58.5'inin gelirinin giderine eşit olduğu, %85.0'ının çekirdek ailede olduğu ve %68.3'ünün il merkezinde yaşadığı belirlenmiştir.

Tablo 2. Çocukların tanıtıcı özellikleri (n=306)

Değişkenler	**Ort.+SS**	**Min-Max**
Yaş ortalama (anne)	**8.8±1.72**	**7-12**
	n	**%**
Cinsiyet		
Kız	165	53.9

Erkek	141	46.1
Eğitim düzeyi		
İlköğretim	249	81.4
Ortaöğretim	57	18.6
Kardeş durumu		
Var	264	86.3
Yok	42	13.7
Çocuğun hastalığı		
Akut	271	88.6
Kronik	35	11.4
Hastanede yatış süresi		
3 gün	143	46.7
4-6 gün	132	43.2
>7 gün	31	10.1
Damar yolu açılma durumu		
Evet	217	70.9
Hayır	89	29.1
Daha önce hastanede yatma deneyimi		
Evet	109	35.6
Hayır	197	64.4

Tablo 2 incelendiğinde, çocukların yaş ortalamasının 8.8±1.72 olduğu ve %53.9'unun kız cinsiyette olduğu belirlenmiştir. Çocukların %81.4'ünün ilköğretime devam ettiği, %86.3'ünün en az bir kardeşi olduğu saptanmıştır. Araştırmaya katılan çocukların %88.6'sının akut hastalık nedeniyle hastanede yattığı, %46.7'sinin hastanede 3 gün kaldığı, %70.9'una damar yolu açıldığı ve %35.6'sının daha önce hastanede yatma deneyimi olduğu belirlenmiştir.

Tablo 3. Tıbbi İşlem Korku Ölçeği ve Psikososyal Semptom Tanılama Ölçeği Puan Dağılımları

Ölçek	**Ort±Std.Sapma**	**Min-Max**
Tıbbi İşlem Korku Ölçeği	62.9±10.6	32-81
İşlemsel	18.7±4.4	9-27
Çevresel	16.7±3.3	7-21
Kişisel	9.1±2.1	3-12
Kişilerarası	18.6±3.7	9-27
Psikososyal Semptom Tanılama Ölçeği	24.2±6.4	12-40
Anksiyete	7.9±2.1	3-12
Umutsuzluk	6.5±1.6	2-10
İletişim Güçlüğü	5.1±3.7	1-50
Öfke Saldırganlık	2.2±1.5	0-7
Regresyon	3.7±1.5	1-6

Tablo 3'de Tıbbi İşlem Korku Ölçeği ve Psikososyal Semptom Tanılama Ölçeği Puan Dağılımları verilmiştir. Tablo 3 incelendiğinde Tıbbi İşlem Korku Ölçeği toplam puan ortalamasının 62.9±10.6 (32-81) olduğu ve Psikososyal Semptom Tanılama Ölçeği toplam puan ortalamasının 24.2±6.4 (12-40) olduğu belirlenmiştir. Tıbbi İşlem Korku Ölçeği alt boyutları puan ortalamaları ise sırasıyla İşlemsel 18.7±4.4, Çevresel 16.7±3.3, Kişisel 9.1±2.1 ve Kişilerarası 18.6±3.7; Psikososyal Semptom Tanılama Ölçeği alt boyutları puan ortalamaları ise sırasıyla Anksiyete 7.9±2.1, Umutsuzluk 6.5±1.6, İletişim Güçlüğü 5.1±3.7, Öfke Saldırganlık 2.2±1.5 ve Regresyon 3.7±1.5 olarak saptanmıştır.

Tablo 4. Çocukların tanıtıcı özelliklerine göre Tıbbi İşlem Korkusu Ölçeği'nin toplam ve alt boyut puan ortalamalarının karşılaştırılması

Özellikler		Tıbbi İşlem Korku Ölçeği				
		İşlemsel	Çevresel	Kişisel	Kişilerarası	Toplam
		Ort.+SS	Ort.+SS	Ort.+SS	Ort.+SS	Ort.+SS
Cinsiyet	**Kadın**	18.53±4.65	16.64±3.51	8.80±2.0	18.98±3.75	62.89±11.16
	Erkek	18.85±4.10	16.86±2.96	9.26±1.97	18.11±3.67	62.93±10.06
	Test /p	t:-0.622 p:0.534	t:-0.104 p:0.917	t:-2.023 **p:0.044**	t:2.036 **p:0.043**	t:-.037 p:0.971
Kardeş durumu	**Kardeşi var**	18.37±4.48	16.78±3.38	8.93±2.0	18.47±3.80	62.50±11.11
	Kardeşi yok	20.59±3.33	15.90±2.26	9.50±1.95	19.23±3.25	65.45±6.63
	Test /p	t:-3.796 **p:0.000**	t:2.154 **p:0.035**	t:-1.701 p:0.090	t:-1.226 p:0.221	t:-2.39 **p:0.019**
Okul düzeyi	**İlköğretim**	18.93±4.27	16.65±3.13	8.93±1.97	18.86±3.71	63.39±10.45
	Ortaöğretim	17.57±4.81	16.68±3.83	9.35±2.11	17.35±3.61	60.80±11.33
	Test /p	t:1.957 p:0.054	t:-0.054 p:0.957	t:-1.414 p:0.158	t:2.786 **p:0.006**	t:1.659 p:0.098
Hastalık türü	**Akut**	18.82±4.51	16.67±3.38	9.03±2.06	18.57±3.84	63.08±11.07
	Kronik	17.60±3.27	16.54±2.14	8.82±1.42	18.60±2.85	61.57±6.41
	Test /p	t:1.980 p:0.053	t:0.317 p:0.752	t:0.767 p:0.446	t:-0.031 p:0.976	t:1.186 p:0.240
Damar yolu açılma durumu	**Evet**	18.07±4.52	16.17±3.24	8.84±2.04	18.17±3.88	61.19±11.20
	Hayır	20.16±3.72	17.83±3.04	9.42±1.83	19.58±3.15	67.08±7.7
	Test /p	t:-3.863 **p:0.000**	t:-4.118 **p:0.000**	t:-2.331 **p:0.020**	t:-3.320 **p:0.001**	t:-4.553 **p:0.000**
Sık hastalık geçirme durumu	**Evet**	17.43±4.05	16.00±3.38	8.62±2.09	17.98±3.44	59.96±10.62
	Hayır	20.16±3.72	16.93±3.18	9.17±1.94	18.82±3.83	64.13±10.44
	Test /p	t:-3.253 **p:0.001**	t:-2.296 **p:0.022**	t:-2.217 **p:0.027**	t:-1.797 p:0.073	t:-3.168 **p:0.002**
Daha önce hastaneye yatma durumu	**Evet**	16.44±4.38	14.97±3.52	8.11±1.99	16.87±3.51	56.40±11.25
	Hayır	19.92±3.90	17.59±2.70	9.50±1.83	19.52±3.52	66.51±8.37
	Test /p	t:-7.148 **p:0.000**	t:-6.747 **p:0.000**	t:-6.146 **p:0.000**	t:-6.321 **p:0.000**	t:-8.915 **p:0.000**
Hastanede kalma süresi	**3 gün**	18.81±4.18	16.81±3.60	9.14±1.93	18.82±3.39	63.65±10.13
	4-6 gün	19.22±4.46	16.75±3.00	9.04±2.15	18.34±4.20	63.25±11.40
	7 ≤	15.77±4.15	15.54±2.50	8.25±1.43	18.48±3.10	58.06±8.48
	Test /p	F:8.196 **p:0.000**	F:2.024 **p:0.134**	F:2.564 p:0.079	F:0.586 p:0.557	F:3.684 **p:0.026**

F: Tek yönlü varyans analizi (ANOVA); t: Bağımsız gruplarda t-testi (student t-test)

Çocukların Tıbbi İşlem Korku Ölçeği puanlarının çeşitli sosyodemografik ve klinik özelliklere göre karşılaştırılması Tablo 4'te sunulmuştur. Cinsiyete göre toplam Tıbbi İşlem Korku Ölçeği puanları arasında anlamlı fark bulunmamıştır ($p>0.05$). Ancak kız çocuklarının kişisel korku alt boyutu puanları erkek çocuklara göre daha düşük (8.80±2.00) ve kişilerarası korku alt boyutu puanları daha yüksek (18.98±3.75) bulunmuştur ($p<0.05$).

Kardeşi olmayan çocukların işlemsel korku (20.59±3.33) ve toplam korku puanları (65.45±6.63), kardeşi olan çocuklara göre anlamlı düzeyde daha yüksektir (p<0.05). Buna karşılık kardeşi olan çocukların çevresel korku puanları daha yüksek bulunmuştur (p<0.05).

Okul düzeyine göre toplam ölçek puanları arasında anlamlı fark saptanmamıştır (p>0.05). Bununla birlikte ilköğretim düzeyindeki çocukların kişilerarası korku puanları ortaöğretim düzeyindeki çocuklardan daha yüksektir (p=0.006). Hastalık türüne göre (akut/kronik) ölçek toplam ve alt boyut puanları arasında anlamlı fark bulunmamıştır (p>0.05).

Damar yolu açılan çocukların işlemsel, çevresel, kişisel, kişilerarası ve toplam korku puanlarının, damar yolu açılmayan çocuklara göre anlamlı düzeyde daha düşük olduğu belirlenmiştir (p<0.05). Sık hastalık geçirmeyen çocukların işlemsel, çevresel, kişisel ve toplam korku puanları, sık hastalık geçiren çocuklara göre anlamlı düzeyde daha yüksek bulunmuştur (p<0.05). Kişilerarası korku alt boyutunda ise gruplar arasında anlamlı fark saptanmamıştır (p>0.05). Daha önce hastaneye yatmamış çocukların işlemsel, çevresel, kişisel, kişilerarası ve toplam korku puanları, daha önce hastaneye yatmış çocuklara göre anlamlı düzeyde daha yüksektir (p<0.001). Hastanede kalış süresine göre işlemsel korku ve toplam korku puanları arasında anlamlı fark bulunmuştur (p<0.05). Yedi gün ve üzerinde hastanede kalan çocukların işlemsel korku (15.77±4.15) ve toplam korku puanları (58.06±8.48), üç gün ve 4–6 gün hastanede kalan çocuklara göre daha düşüktür. Çevresel, kişisel ve kişilerarası korku alt boyutlarında ise kalış süresine göre anlamlı fark saptanmamıştır (p>0.05).

Tablo 5. Çocukların tanıtıcı özelliklerine göre Hastanede Yatan Çocuklar İçin Psikososyal Semptomları Tanılama Ölçeği'nin toplam ve alt boyut puan ortalamalarının karşılaştırılması

Özellikler			**Psikososyal Semptomları Tanılama Ölçeği**				
		Anksiyete	**Umutsuzluk**	**İletişim güçlüğü**	**Öfke/ saldırganlık**	**Regresyon**	**Toplam**
		Ort.+SS	**Ort.+SS**	**Ort.+SS**	**Ort.+SS**	**Ort.+SS**	**Ort.+SS**
Cinsiyet	**Kadın**	7.74±1.96	6.50±1.58	5.20±5.18	2.15±1.41	3.62±1.10	24.66±6.00
	Erkek	8.28±2.12	6.41±1.73	4.79±4.06	2.19±1.70	3.78±1.21	25.19±6.77
	Test /p	t:-2.287 **p:0.023**	t:0.483 p:0.630	t:0.752 p:0.453	t:-0.230 p:0.818	t:-1.175 p:0.241	t:-.712 p:0.477
Kardeş durumu	**Kardeşi var**	8.01±2.08	6.46±1.64	5.06±5.02	2.21±1.48	3.64±1.18	24.88±6.39
	Kardeşi yok	7.83±1.84	6.45±1.69	4.69±1.42	1.90±1.91	4.02±0.89	25.04±6.20
	Test /p	t:0.543 p:0.587	t:0.035 p:0.972	t:0.478 p:0.633	t:1.223 p:0.222	t:-2.428 **p:0.018**	t:-.152 p:0.879
Okul düzeyi	**İlköğretim**	7.89±2.05	6.44±1.60	5.19±5.15	2.19±1.61	3.62±1.12	24.80±6.29
	Ortaöğretim	8.42±2.02	6.50±1.86	4.22±1.28	2.10±1.23	4.01±1.23	25.35±6.68
	Test /p	t:-1.749 p:0.081	t:-0.243 p:0.809	t:1.400 p:0.162	t:0.453 p:0.651	t:-2.341 **p:0.020**	t:-0.581 p:0.562
Hastalık türü	**Akut**	8.04±2.12	6.52±1.64	4.89±4.13	2.18±1.57	3.75±1.16	25.08±6.41
	Kronik	7.57±1.37	6.00±1.66	5.91±7.83	2.14±1.35	3.22±1.00	23.57±5.83
	Test /p	t:1.790 p:0.079	t:1.758 p:0.080	t:-1.206 p:0.229	t:0.136 p:0.892	t:2.562 **p:0.011**	t:1.322 p:0.187
Damar yolu açılma durumu	**Evet**	7.73±2.01	6.38±1.62	5.03±5.52	1.98±1.58	3.55±1.15	24.04±6.34
	Hayır	8.61±2.01	6.64±1.72	4.95±1.24	2.65±1.36	4.04±1.08	27.01±5.94

	Test /p	t:-3.468 **p:0.001**	t:-1.218 p:0.224	t:0.138 p:0.890	t:-3.493 **p:0.001**	t:-3.529 **p:0.001**	t:-3.782 **p:0.000**
Sık hastalık geçirme durumu	**Evet**	7.30±1.69	6.05±1.47	6.22±8.29	1.62±1.20	3.18±1.14	22.71±5.50
	Hayır	8.28±2.12	6.62±1.69	4.50±1.40	2.40±1.62	3.90±1.10	25.82±6.48
	Test /p	t:-4.279 **p:0.000**	t:-2.798 **p:0.005**	t:1.947 **p:0.055**	t:-4.666 **p:0.000**	t:-5.150 **p:0.000**	t:-3.993 **p:0.000**
Daha önce hastaneye yatma durumu	**Evet**	7.26±1.93	596±2.00	5.06±6.36	1.81±1.51	3.12±1.06	22.27±6.62
	Hayır	8.39±2.01	6.73±1.34	4.98±3.47	2.37±1.54	4.01±1.08	26.36±5.73
	Test /p	t:-4.771 **p:0.000**	t:-4.010 **p:0.000**	t:0.096 p:0.888	t:-3.059 **p:0.002**	t:-6.848 **p:0.000**	t:-5.422 **p:0.000**
Hastanede kalma süresi	**3 gün**	8.03±2.06	6.39±1.69	5.59±6.68	2.31±1.46	3.74±1.20	25.20±6.29
	4-6 gün	8.00±2.11	6.47±1.68	4.48±1.40	1.95±1.70	3.75±1.14	24.62±6.75
	7 ≤	7.77±1.74	6.70±1.29	4.58±1.28	2.48±1.09	3.19±0.83	24.70±4.91
	Test /p	F:0.206 p:0.814	F:0.481 p:0.619	F:2.074 p:0.128	F:2.551 p:0.080	F:3.301 **p:0.038**	F:0.302 p:0.740

F: Tek yönlü varyans analizi (ANOVA); t: Bağımsız gruplarda t-testi (student t-test)

Çocukların Psikososyal Semptomları Tanılama Ölçeği puanlarının sosyodemografik ve klinik özelliklere göre karşılaştırılması Tablo 5'te sunulmuştur.

Cinsiyete göre ölçek toplam puanları arasında anlamlı fark bulunmamıştır (p>0.05). Bununla birlikte erkek çocukların anksiyete puan ortalamaları (8.28±2.12), kız çocuklara göre (7.74±1.96) anlamlı düzeyde daha yüksektir (p=0.023). Umutsuzluk, iletişim güçlüğü, öfke/saldırganlık ve regresyon alt boyutlarında cinsiyete göre anlamlı fark saptanmamıştır (p>0.05).

Kardeş durumuna göre ölçek toplam puanları ve çoğu alt boyut puanı açısından anlamlı fark bulunmamıştır (p>0.05). Ancak kardeşi olmayan çocukların regresyon puanları (4.02±0.89), kardeşi olan çocuklara göre (3.64±1.18) anlamlı düzeyde daha yüksektir (p=0.018). Okul düzeyine göre toplam ölçek puanları arasında anlamlı fark bulunmamıştır (p=0.562). Ortaöğretim düzeyindeki çocukların regresyon puanları (4.01±1.23), ilköğretim düzeyindeki çocuklara göre (3.62±1.12) anlamlı olarak daha yüksektir (p=0.020). Diğer alt boyutlarda anlamlı fark saptanmamıştır (p>0.05).

Hastalık türüne göre toplam ölçek puanları arasında anlamlı fark bulunmamıştır (p=0.187). Bununla birlikte akut hastalığı olan çocukların regresyon puanları (3.75±1.16), kronik hastalığı olan çocuklara göre (3.22±1.00) anlamlı düzeyde daha yüksektir (p=0.011). Damar yolu açılmayan çocukların anksiyete (8.61±2.01), öfke/saldırganlık (2.65±1.36), regresyon (4.04±1.08) ve toplam ölçek puanları (27.01±5.94), damar yolu açılan çocuklara göre anlamlı düzeyde daha yüksektir (sırasıyla p=0.001, p=0.001, p=0.001 ve p<0.001). Umutsuzluk ve iletişim güçlüğü alt boyutlarında anlamlı fark bulunmamıştır (p>0.05).

Sık hastalık geçirmeyen çocukların anksiyete, umutsuzluk, öfke/saldırganlık, regresyon ve toplam ölçek puanları; sık hastalık geçiren çocuklara göre anlamlı düzeyde daha yüksektir (p<0.05). İletişim güçlüğü alt boyutunda ise gruplar arasında anlamlı fark saptanmamıştır (p=0.055).

Daha önce hastaneye yatmamış çocukların anksiyete (8.39±2.01), umutsuzluk (6.73±1.34), öfke/saldırganlık (2.37±1.54), regresyon (4.01±1.08) ve toplam ölçek puanları (26.36±5.73), daha önce hastaneye yatmış çocuklara göre anlamlı düzeyde daha yüksektir (p<0.01). İletişim güçlüğü alt boyutunda anlamlı fark bulunmamıştır (p=0.888). Hastanede kalış süresine göre toplam ölçek puanları

arasında anlamlı fark bulunmamıştır (p=0.740). Yalnızca regresyon alt boyutunda anlamlı fark saptanmış (p=0.038) ve en düşük regresyon puanının yedi gün ve üzerinde hastanede kalan çocuklarda olduğu görülmüştür (3.19±0.83). Diğer alt boyutlarda anlamlı fark bulunmamıştır (p>0.05).

Tablo 6. Tıbbi İşlem Korku Ölçeği ve Psikososyal Semptom Tanılama Ölçeği Arasındaki ilişkinin incelenmesi

		Tıbbi İşlem Ölçeği	İşlemsel	Çevresel	Kişisel	Kişiler-Arası
Psiko-sosyal Semptom Ölçeği	**r**	0.75	0.67	0.65	0.40	0.57
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Anksiyete	**r**	0.69	0.61	0.65	0.43	0.45
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Umutsuzluk	**r**	0.53	0.51	0.43	0.30	0.50
	P	**<0.001**	**<0.001**	**<0.001**	**0.004**	**<0.001**
İletişim Güçlüğü	**r**	0.35	0.30	0.32	0.11	0.36
	P	**<0.001**	**<0.001**	**<0.001**	0.1	**<0.001**
Öfke Saldırganlık	**r**	0.55	0.47	0.53	0.30	0.45
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Regresyon	**r**	0.60	0.58	0.51	0.46	0.47
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

*Pearson Korelasyon, p<0,05 anlamlılık

Tıbbi İşlem Korku Ölçeği ve Psikososyal Semptom Tanılama Ölçeği ilişki durumu incelendiğinde, Psiko-sosyal Toplam ölçek puanı ile Tıbbi İşlem Korku Ölçeği toplam puanı arasında 0.75, Tıbbi İşlem alt ölçek işlemsel toplam puanı arasında 0.67, Tıbbi İşlem alt ölçek çevresel toplam puanı arasında 0.65, Tıbbi İşlem alt ölçek kişisel toplam puanı arasında 0.40 ve Tıbbi İşlem alt ölçek kişiler arası toplam puanı arasında ise 0.57 ilişki katsayılı pozitif yönlü anlamlı ilişki saptanmıştır (p<0,05). Tıbbi İşlem Korku Ölçeği toplam puanı ile Psiko-sosyal alt ölçekleri Anksiyete Toplam puanı arasında 0.69, Umutsuzluk Toplam puanı arasında 0.53, iletişim güçlüğü Toplam puanı arasında 0.35, öfke saldırganlık Toplam puanı arasında 0.55, regresyon Toplam puanı arasında ise 0,60 katsayılı pozitif yönlü anlamlı ilişki bulunmuştur (p<0.05). Tıbbi İşlem Alt ölçek işlemsel toplam puanı ile Psiko-sosyal alt ölçekleri Anksiyete Toplam puanı arasında 0.61, Umutsuzluk Toplam puanı arasında 0.51, iletişim güçlüğü Toplam puanı arasında 0.30, öfke saldırganlık Toplam puanı arasında 0.47, regresyon Toplam puanı arasında ise 0.58 katsayılı pozitif yönlü anlamlı ilişki bulunmuştur (p<0.05). Tıbbi İşlem Alt ölçek çevresel toplam puanı ile Psiko-sosyal alt ölçekleri Anksiyete Toplam puanı arasında 0.65, Umutsuzluk Toplam puanı arasında 0.43, iletişim güçlüğü Toplam puanı arasında 0.32, öfke saldırganlık Toplam puanı arasında 0.53, regresyon Toplam puanı arasında ise 0.51 katsayılı pozitif yönlü anlamlı ilişki saptanmıştır (p<0.05). Tıbbi İşlem Alt ölçek kişisel toplam puanı ile Psiko-sosyal alt ölçekleri Anksiyete Toplam puanı arasında 0.43, Umutsuzluk Toplam puanı arasında 0.30, öfke saldırganlık Toplam puanı arasında 0.30, regresyon Toplam puanı arasında ise 0.46 katsayılı pozitif yönlü anlamlı ilişki belirlenmiştir (p<0.05). Tıbbi İşlem Alt ölçek kişiler arası toplam puanı ile Psiko-sosyal alt ölçekleri Anksiyete Toplam puanı arasında 0.45, Umutsuzluk Toplam puanı arasında 0.50, iletişim güçlüğü toplam puan arasında 0.36, öfke saldırganlık Toplam puanı arasında 0.45, regresyon Toplam puanı arasında ise 0.47 katsayılı pozitif yönlü anlamlı ilişki belirlenmiştir (p<0.05).

TARTIŞMA

Çalışmada Tıbbi İşlem Korku Ölçeği toplam puan ortalamasının 62.9±10.6 olması, çocukların hastane ortamı ve uygulanan işlemler nedeniyle belirgin düzeyde korku yaşadığını göstermektedir. Hastane ortamındaki bilinmezlik, ağrı beklentisi, ebeveynden ayrılma, kontrol kaybı ve yabancı sağlık personeli ile karşılaşma gibi durumların çocuklarda korku ve kaygıyı artırdığı bilinmektedir. World

Health Organization (2021) ve United Nations Children's Fund (2021) tarafından vurgulanan çocuk dostu sağlık hizmeti yaklaşımı, bu korkuların azaltılmasının çocuk sağlığı bakımının temel bileşenlerinden biri olduğunu belirtmektedir. Ayrıca son yıllarda yapılan çalışmalar, hastaneye yatışın özellikle okul çağındaki çocuklarda duygusal stres ve davranış değişiklikleri ile ilişkili olduğunu göstermektedir (Birnie,. et al. 2018). Psikososyal Semptom Tanılama Ölçeği toplam puan ortalamasının 24.2±6.4 olması, çocukların hastane sürecinde orta düzeyde psikososyal belirti yaşadığını ortaya koymaktadır. En yüksek puanların anksiyete ve umutsuzluk alt boyutlarında bulunması, çocukların hastanede belirsizlik ve kontrol kaybına karşı en yoğun duygusal tepkilerinin kaygı ve çaresizlik olduğunu düşündürmektedir. Pediatrik psikoloji literatürü, ağrı ve korkunun çocukların baş etme kapasitesini azaltarak davranışsal ve duygusal semptomları artırdığını göstermektedir. (Pate et al., 2023; Uman et al., 2019).

Çalışmada daha önce hastaneye yatmamış, sık hastalık geçirmeyen ve damar yolu açılmayan çocukların hem tıbbi işlem korkusu hem de psikososyal semptom puanlarının daha yüksek bulunması dikkat çekicidir. Bu bulgu, çocukların hastane deneyimine ilişkin tanışıklık kazandıkça süreçle daha etkili baş edebildiklerini düşündürmektedir. American Academy of Pediatrics (2022), çocukların hastane deneyimlerine hazırlanmasının ve gelişim düzeyine uygun açıklamalar yapılmasının korkuyu azaltmada etkili olduğunu bildirmektedir. Önceki deneyimler, çocuğun öngörülebilirlik duygusunu artırarak tehdit algısını azaltabilir. Bu sonuç, Thrane ark.'nın (2024) hastanede yatan okul çağı çocuklarıyla gerçekleştirdikleri çalışmanın bulgularıyla da desteklenmektedir. Araştırmacılar, hastane ortamına ve uygulanan işlemlere aşinalığın çocukların belirsizlik algısını azalttığını, buna bağlı olarak anksiyete düzeylerinin düştüğünü ve hastaneye uyumlarının kolaylaştığını bildirmiştir. Benzer şekilde Birnie ve ark.'nın (2018) sistematik derlemesinde, çocukların işlem öncesinde bilgilendirilmesi ve önceki deneyimlerden yararlanılmasının prosedürel korku ve distresi anlamlı ölçüde azalttığı gösterilmiştir. Bu bulgular birlikte değerlendirildiğinde, hastane deneyiminin çocuklarda bir öğrenme ve uyum süreci oluşturduğu; önceki deneyimlerin ve uygun hazırlığın çocukların hem tıbbi işlem korkusunu hem de psikososyal semptomlarını azaltmada koruyucu rol oynadığı söylenebilir.

Hastanede kalış süresi arttıkça tıbbi işlem korkusu ve regresyon puanlarının azalması da uyum sürecini destekleyen bir bulgudur. Özellikle yedi gün ve üzeri hastanede kalan çocukların korku düzeylerinin daha düşük olması, zaman içinde çevreye ve sağlık personeline alışmanın psikolojik uyumu kolaylaştırdığını göstermektedir. Bununla birlikte uzun süreli yatışların farklı psikososyal riskler yaratabileceği de unutulmamalıdır; bu nedenle her çocuk bireysel olarak değerlendirilmelidir.

Araştırmanın en önemli bulgusu, tıbbi işlem korkusu ile psikososyal semptomlar arasında güçlü düzeyde pozitif ilişki bulunmasıdır (r=0.75). Korelasyon katsayısının büyüklüğü, tıbbi işlem korkusu arttıkça çocukların psikososyal sorunlarının belirgin şekilde arttığını göstermektedir. Özellikle anksiyete ile toplam korku puanı arasındaki yüksek ilişki (r=0.69), korkunun çocukların duygusal durumunu doğrudan etkilediğini düşündürmektedir. Regresyon (r=0.60), öfke-saldırganlık (r=0.55) ve umutsuzluk (r=0.53) ile saptanan ilişkiler de çocukların korkularını davranışsal belirtiler yoluyla dışa vurduğunu göstermektedir. Bu bulgular, pediatrik ağrı ve stres araştırmalarında bildirilen "korku–ağrı–anksiyete döngüsü" ile uyumludur; korku ağrı algısını artırmakta, artan ağrı ise psikososyal belirtileri güçlendirmektedir. Bu bulgular, International Association for the Study of Pain (2022) tarafından tanımlanan "korku–ağrı–anksiyete döngüsü" ile uyumludur. Bu modele göre çocuğun işlem öncesi yaşadığı korku, ağrı beklentisini ve algılanan ağrı şiddetini artırmakta; artan ağrı deneyimi ise kaygı, çaresizlik ve davranışsal sorunları daha da güçlendirmektedir. Ayrıca Noel ve ark. (2012), çocukluk döneminde yaşanan ağrı ve korku deneyimlerinin kısa dönemde duygusal distrese, uzun dönemde ise sağlık bakımına yönelik kaçınma davranışlarına yol açabildiğini bildirmiştir.

Tıbbi işlem korkusunun alt boyutlarının tümünün psikososyal semptomlarla ilişkili olması, korkunun çok boyutlu bir deneyim olduğunu göstermektedir. İşlemsel ve çevresel korku alt boyutlarının anksiyete ile güçlü ilişkisi, çocukların özellikle iğne uygulamaları, ağrılı girişimler, tıbbi cihazlar ve yabancı hastane ortamına karşı duyarlı olduklarını düşündürmektedir. Birnie, ve ark.nın (2018) Cochrane sistematik derlemesinde, işlem öncesi korku ve kaygının çocuklarda ağrı algısını ve

davranışsal distresi anlamlı düzeyde artırdığı gösterilmiştir. Kişilerarası korkunun umutsuzluk ve iletişim güçlüğü ile ilişkili bulunması ise sağlık profesyonelleriyle kurulan ilişkinin çocukların duygusal iyilik hali üzerinde belirleyici olduğunu ortaya koymaktadır. Coyne ve ark. (2016), aile merkezli bakım yaklaşımında çocuk ve aile ile güvene dayalı iletişimin çocuğun kontrol duygusunu güçlendirdiğini ve hastane deneyimini olumlu yönde etkilediğini bildirmiştir.

Klinik uygulama açısından bu bulgular, çocukların tıbbi işlem korkusunun sistematik olarak değerlendirilmesi gerektiğini göstermektedir. Hemşireler; gelişimsel hazırlık, terapötik oyun, dikkat dağıtma, ebeveyn katılımı, gevşeme teknikleri ve yaşa uygun bilgilendirme gibi kanıta dayalı girişimlerle korku ve psikososyal belirtileri azaltabilir. American Academy of Pediatrics (2022), çocuk yaşam uzmanlığı hizmetleri ve hazırlık programlarının prosedürel anksiyeteyi azaltmada etkili olduğunu vurgulamaktadır. Benzer şekilde Koller & Goldman (2012) dikkat dağıtma tekniklerinin çocukların ağrı ve korku düzeylerini anlamlı biçimde azalttığını bildirmiştir. Bu doğrultuda özellikle ilk kez hastaneye yatan, hastane deneyimi olmayan ve yüksek korku puanı gösteren çocukların erken dönemde belirlenmesi ve yapılandırılmış psikososyal destek programlarına yönlendirilmesi önerilmektedir.

SONUÇ

Araştırmanın sonuçları, tıbbi işlem korkusunun çocukların psikososyal uyumunu etkileyen temel belirleyicilerden biri olduğunu göstermektedir. Çocuk dostu bakım ortamlarının oluşturulması, aile katılımının güçlendirilmesi ve hemşirelik girişimlerinin bireyselleştirilmesi, hem korkunun hem de psikososyal semptomların azaltılmasına katkı sağlayabilir. Bu nedenle pediatri hemşireliğinde tıbbi işlem korkusunun erken tanılanması ve uygun girişimlerle yönetilmesi, çocukların hastane deneyimlerinin iyileştirilmesinde kritik öneme sahiptir.

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WHAT DOES THE GUTMANN METHOD REVEAL ABOUT ALBANIA'S NON-OBSERVED ECONOMY?

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Abstract

This paper provides an in-depth analysis of the non-observed economy in Albania, using the monetary aggregate approach, widely known as the Gutmann approach. The primary objective is to estimate the size and dynamics of undeclared economic activities over the period 2006–2024, using official data published by the Bank of Albania. By focusing on currency demand as an indirect indicator of undeclared activity, the study captures fluctuations in the use of cash that are typically associated with hidden transactions outside the formal economy. The analysis highlights that, despite notable progress in payment digitalization and the strengthening of the regulatory and institutional framework, the non-observed economy remains a persistent structural challenge. Its presence continues to generate significant implications for macroeconomic stability, including distortions in key economic indicators, reduced effectiveness of monetary policy transmission, and challenges in accurately measuring economic performance. Furthermore, high levels of non-observed economy undermine fiscal capacity by limiting tax collection and widening the tax gap, thereby constraining public investment and the provision of essential services. In addition, the study emphasizes the social dimension of hidden economy, particularly its impact on equity and fairness. Undeclared activities often create unequal conditions among economic agents, disadvantaging compliant businesses and workers while fostering inefficiencies in the allocation of resources. Through a rigorous empirical approach, this research aims to contribute to a deeper understanding of the scale and evolution of the non-observed economy in Albania. It also seeks to provide evidence-based policy recommendations, focusing on measures to promote formalization, enhance financial transparency, and strengthen institutional enforcement mechanisms to support more sustainable and inclusive economic development.

Keywords: Non-Observed Economy, monetary aggregate, Gutmann Approach, currency demand

1. INTRODUCTION

The Non-Observed Economy (NOE), also known as the informal, shadow, or underground economy, represents one of the most significant challenges to macroeconomic stability and sustainable development in transition economies. The NOE includes activities that are legal in nature but are not declared to avoid taxes, social contributions, or to bypass labor regulations, as well as illegal activities. This phenomenon is universal, but its size and characteristics vary significantly across countries, particularly between developed or developing economies. Measuring and analyzing NOE is an essential task for the formulation of effective economic policies for several reasons. However, measuring it accurately remains extremely difficult. Failure to capture a significant portion of economic activity leads to distorted representation of macroeconomic indicators, which negatively affects several key areas.

First, it creates a distorted picture of macroeconomic indicators; if a large part of production is not observed, the official GDP underestimates the real purchasing power and well-being of the population. Second, the NOE causes a "tax gap", reducing revenues in the state budget and limiting the government's ability to provide quality public services and infrastructure investments (Hallunovi, A., et al 2023). Third, in terms of social justice and competition, it creates unfair competition between formal businesses that pay taxes and informal ones that operate at lower costs. Fourth, for monetary policy, the size of NOE affects the demand for money in circulation and its velocity of circulation, making it more difficult for the Central Bank to accurately assess the effectiveness of its monetary instruments. Moreover, undeclared work deprives workers of social rights and legal protection. Therefore, an accurate assessment of NOE is a prerequisite for sustainable and inclusive economic development.

In Albania, this phenomenon has deep roots linked to the radical changes in the economic system following the 1990s, in which the transition from a centrally planned economy to a market economy was accompanied by institutional weaknesses, a lack of a regulatory framework, and tax evasion. In transition economies like Albania, the NOE is not merely a statistical discrepancy but a structural feature of the socioeconomic landscape, shaped by decades of institutional shifts, varying levels of tax morale, and the evolution of the private sector.

According to recent studies, the size of this sector in Albania has fluctuated around 30-35% of GDP over the last two decades, a figure significantly higher than the average for European Union (EU) countries (Asllani, A., et al, 2025; Schneider, F., 2023). The main goal of this

paper is to assess the size and dynamics of undeclared economic activities during the period 2010–2024, using official data from the Bank of Albania. The analysis highlights that, despite significant progress in the digitalization of payments and the strengthening of the regulatory framework, the non-observed economy remains a challenge with important implications for macroeconomic stability, fiscal revenue collection and social justice. Through an empirical approach, this study aims to contribute to a better understanding of the phenomenon and to provide evidence-based policy recommendations for its effective addressing.

2. THEORETICAL FRAMEWORK: THE MONETARY AGGREGATE METHOD

2.1. Origin and Evolution of the Gutmann Method

The monetary aggregate method, also known as the monetary approach, is one of the most widely used indirect methods for estimating the size of the NOE. Non-observed economic activities (informal, hidden or parallel) cause deviations in monetary aggregates, which can be identified through measurement methods based on this theory. It was first proposed by Peter Gutmann in 1977, who argued that undeclared economic activity relies mainly on cash transactions to avoid detection by authorities. The basic idea is that cash leaves no auditable trace, unlike bank, check, or credit card transactions. Gutmann noticed a sudden increase in the ratio of currency in circulation to deposits in the United States despite the development of the banking system and the growth of non-cash payment instruments. He interpreted this as an indicator of the expansion of the non-observed economy. Since then, the method has been developed and refined by other economists such as Edgar Feige (1979) and Vito Tanzi in the 1980s, becoming an important tool in the literature on the non-observed economy. Tanzi introduced a currency demand function, where the demand for currency in circulation is no longer seen as constant, but as dependent on economic factors such as the tax burden, interest rates and income levels. Through the use of econometric methods, Tanzi was able to isolate the part of the demand for currency in circulation that is specifically related to motives for tax evasion, thus distinguishing more clearly the use of money in the formal economy from the non-observed one. This approach, known as the Tanzi method, represents a more rigorous and precise evolution of Gutmann's initial idea.

Although it has received criticism for its simplistic assumptions, it remains a valuable starting point for preliminary and comparative assessments.

2.2. Basic Assumptions, Strengths, and Limitations of the Method

By linking monetary theory with actual economic behavior, the approach provides a theoretical foundation for estimating the NOE. The monetary aggregates method relies on several fundamental assumptions (Gutmann, 1977; Spiro, 1994) which are also the source of its limitations.

First, it assumes that cash is the exclusive medium of exchange in the non-observed economy. This assumption is quite rigid, since in reality, even hidden transactions may use other forms of payment, especially with the development of new financial technologies and digitalization. **Second,** the Gutmann approach requires the definition of a base period in which the NOE is assumed to be minimal or non-existent. The choice of this period is critical, since estimates of the size of NOE are very sensitive to it.

Third, it assumes that the velocity of money is the same in the formal and informal sectors. This assumption is also questionable, as hidden activity may have a higher or lower velocity, depending on the nature of the transactions. In addition, Porter and Weinbach (1999) and Spiro (1994) have argued that changes in financial technology, such as the spread of credit cards, automated teller machines (ATMs), and electronic payments, may affect the demand for currency in circulation regardless of the level of informality, making the interpretation of the C/D ratio more complex.

Despite its limitations, the approach offers a clear, practical, and intuitively grounded framework for analyzing the non-observed economy, particularly in contexts where detailed data are scarce. By relying on widely available monetary aggregates such as currency in circulation and deposits, it enables consistent estimation over long time horizons and facilitates comparability across periods. Its relative simplicity makes it easy to implement and interpret, while also serving as a foundational framework for the development of more advanced econometric models. Importantly, the approach provides valuable insights for policymakers by highlighting the relationship between taxation, monetary behavior, and the dynamics of informality.

3. METHODOLOGY

3.1. Conceptual Framework

Following Gutmann (1977) and Davidescu (2013), this study estimates NOE for Albania using Gutmann's simple currency ratio approach. It decomposes the total stock of currency (C) and demand deposits (D) into their observed and non-observed components:

$$\mathbf{C = C_o + C_u} \quad \mathbf{(1)}$$

$$\mathbf{D = D_o + D_u} \quad \mathbf{(2)}$$

where: subscript (o) denotes the observed (formal) sector and u the non-observed (informal) sector. The ratio of currency to demand deposits in each sector is defined as:

$$\mathbf{k_o = C_o / D_o} \quad \textit{(observed sector ratio, assumed constant = } k_o\textit{)} \quad \mathbf{(3)}$$

Equation (3) defines k_o as the share of currency in circulation that formal-sector agents choose to hold relative to their deposits. Gutmann's key assumption is that this ratio is structurally stable over time: households and businesses maintain a broadly constant preference between cash and demand deposits, driven by transaction habits and financial development. It is precisely this stability that makes k_o suitable as a baseline (k_0): any sustained rise of the observed k above k_0 signals the presence of additional, unrecorded "cash demand" that cannot be explained by normal formal-sector behaviour.

$$\mathbf{k_u = C_u / D_u} \quad \textit{(non-observed sector ratio, assumed} \rightarrow \infty\textit{, since } D_u = 0\textit{)} \quad \mathbf{(4)}$$

Equation (4) captures the behaviour of agents operating in the non-observed sector. The characteristic of "informal" transactions, according to Gutmann (1977), is that they are settled exclusively in cash. Agents avoid bank accounts because deposits create a traceable record that fiscal and law-enforcement authorities can inspect. Consequently, the demand deposits of the non-observed sector are assumed to be zero ($D_u = 0$). Mathematically, dividing any positive cash stock by zero yields infinity ($k_u \rightarrow \infty$), which simply formalizes the idea that informal agents hold cash in unbounded proportion to their (non-existent) deposits. The practical implication is straightforward: **all** currency held above the formal-sector baseline k_0 is attributed to NOE and none of it passes through the banking system.

Under the simplifying assumptions of the approach (exclusive cash use in the informal sector, constant k_0, and equal velocity $\beta = 1$), the formula for estimating the size of the non-observed economy simplifies to:

Table1. Main Calculation Steps of the Gutmann Method

Step	Formula	What does it measure?
1	**$k^* = k_t - k_0$**	Excess currency in circulation above the baseline level
2	**Illegal C = MAX($k^* \times D$, 0)**	Informal monetary stock
3	**Legal C = C − Illegal C**	Currency in circulation used in the formal economy
4	**v = GNP / M1**	Velocity of money
5	**NOE = Illegal C × v**	NOE

Source: *Author's elaboration based on Gutmann (1977) and Tanzi (1983)*

where:

$\mathbf{k_t}$ = actual C/D ratio in year t;

$\mathbf{k_0}$ = C/D ratio in the base year (no NOE assumed);

k* = excess currency ratio attributed to non-observed activity;

v = income velocity of money (GNP/M1);

NOE expressed in monetary terms and as % of GNP.

For example: Lets suppose $\mathbf{k_0 = 0.986}$ (base year 2007). In year 2009, $\mathbf{k_{2009} = 1.390}$. The excess k* = $\mathbf{k_{2009} - k_0}$ = 1.390 − 0.986 = 0.4. This means that, for every ALL 1,000 of demand deposits, ALL 400 of "extra" cash is circulating beyond what normal and formal behaviour would predict. Under Gutmann's assumptions, this ALL 400 is entirely in the hands of NOE participants. Multiplying by total deposits gives the stock of illegal currency; multiplying further by the income velocity of money converts that stock into a flow estimate of NOE.

Step 2 - *Illegal Currency = MAX ($k^* \times D_t$, 0)* needs particular attention. The expression $k^* \times D_t$ translates the excess currency ratio into an absolute monetary stock. Since $k^* = k_t - k_0$ represents the number of additional currency units circulating per unit of deposits beyond the observed sector baseline, multiplying by total deposits D_t yields the aggregate stock of cash that cannot be accounted for by normal formal-sector transaction behaviour.

In other words, it answers the question: given today's deposit base, ***how much more cash is in circulation than the formal economy structurally requires?***

The MAX operator serves as a non-negativity constraint. It becomes active whenever k_t falls below k_0, producing a negative k*. Economically, a negative k* would imply a negative stock of illegal currency, a mathematical impossibility.

In practice, $k_t < k_0$ can happen for two reasons:

1) the NOE is genuinely below its base-year level, or;
2) as documented in Albania after 2013, the C/D ratio has declined structurally due to financial development factors unrelated to informality (remittance-driven deposit growth, payment digitalization).

In both cases, MAX sets the estimate to zero, preventing the formula from producing nonsensical results.

A practical example is illustrated below. In 2009, k* = 0.4 and D_t = 150,884 Mln ALL, yielding illegal currency of approximately ALL 60,296 Mln — a meaningful positive estimate. By contrast, in 2023, $k_t = 0.45 < k_0 = 0.99$, so k* = −0.54 and the MAX operator forces the estimate to zero. This zero does not mean the NOE disappeared; it means the structural preconditions for the Gutmann method to detect it are no longer met.

Interpretation of MAX ($k^* \times D_t$, 0):

• $k_t > k_0 \rightarrow k^* > 0 \rightarrow$ excess currency in circulation exists → MAX returns the positive value → NOE is estimated

• $k_t = k_0 \rightarrow k^* = 0 \rightarrow$ no excess currency in circulation → MAX returns zero → NOE = 0 (base year by definition)

• $k_t < k_0 \rightarrow k^* < 0 \rightarrow$ k below baseline → MAX returns zero → method cannot detect NOE

3.2. Selection of the Base Year

The choice of the base year is one of the most critical and debated elements of the Gutmann method (Spiro, 1994). The base year should represent a period in which NOE is assumed to be minimal and the C/D ratio reflects only the structural demand for cash in the formal economy. Different choices of base year yield substantially different NOE estimates, which is a well-documented limitation in the literature (Davidescu, 2013).

For this study, 2007 is selected as the base year, for two reasons.

First, it registers the minimum value of the C/D ratio within the structurally stable period 2006–2012 (k_0 = 0.986), representing the lowest observed level of "currency in circulation" before the period of major structural distortions.

Second, this period precedes the significant increase in remittances and the rapid expansion of the banking system that characterize the period after 2013. The stability of the C/D ratio during 2006–2012 (range: 0.986–1.390) satisfies the methodological requirement of a structurally constant k_0.

3.3. Data Sources and Variable Definitions

The analysis uses annual data for the period 2006–2024, sourced exclusively from official publications of the Bank of Albania and the Albanian Institute of Statistics (INSTAT). The variables used are defined as follows:

Table2. Definition of Variables and Data Sources

Variable	Definition	Source
C	Currency outside banking system	Bank of Albania
D	Demand deposits	Bank of Albania
M1	Monetary Aggregate M1	Bank of Albania
GNP	Gross National Product at current prices	INSTAT, National Accounts
v	Income velocity of money = GNP / M1	Calculated by author
k	C/D ratio = currency-to-deposit ratio	Calculated by author

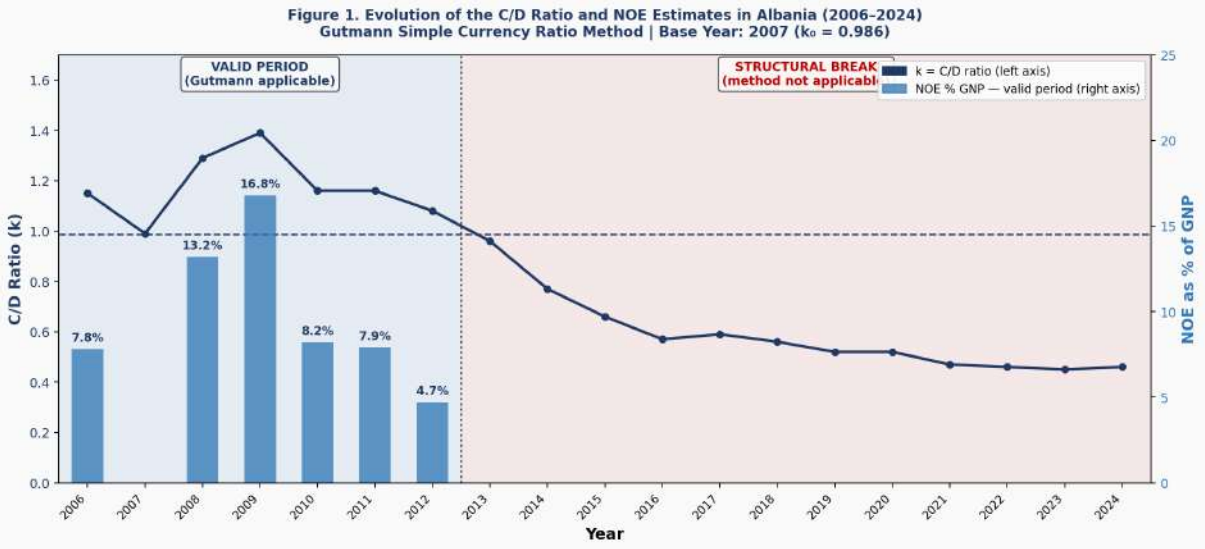
Source: *Author's compilation*

4. EMPIRICAL RESULTS AND STRUCTURAL ANALYSIS

4.1. Evolution of the C/D Ratio (2006–2024)

Table 3 presents the full dataset and calculated values of the C/D ratio for the period 2006–2024. Two phases are clearly identifiable in the data.

Figure 1. Evolution of the C/D Ratio and NOE Estimates in Albania (2006–2024)



***Source**: Bank of Albania; INSTAT. Author's calculations*

Year	C (Mln ALL)	D (Mln ALL)	k = C/D	k* = k−k₀	Illegal Currency (Mln ALL)	v	NOE (Mln ALL)	NOE % GNP
2006	163,264	141,471	1.15	0.168	23,797	2.46	58,443	**7.8%**
2007	154,956	157,182	0.99	0.000	0	2.70	0	**0.0%**
2008	195,817	152,159	1.29	0.301	45,813	2.80	128,320	**13.2%**
2009	209,044	150,884	1.39	0.400	60,297	2.85	171,662	**16.8%**
2010	195,059	167,840	1.16	0.176	29,596	2.86	84,769	**8.2%**
2011	194,923	168,727	1.16	0.169	28,585	2.88	82,282	**7.9%**
2012	192,705	177,748	1.08	0.098	17,474	2.79	48,836	**4.7%**
2013	198,893	206,611	0.96	0.000	—	—	—	**n/a**
2014	217,666	283,513	0.77	0.000	—	—	—	**n/a**
2015	230,602	347,423	0.66	0.000	—	—	—	**n/a**
2016	249,415	436,145	0.57	0.000	—	—	—	**n/a**
2017	275,281	463,726	0.59	0.000	—	—	—	**n/a**
2018	275,285	492,668	0.56	0.000	—	—	—	**n/a**
2019	291,409	557,218	0.52	0.000	—	—	—	**n/a**
2020	344,560	662,534	0.52	0.000	—	—	—	**n/a**

Year	C (Mln ALL)	D (Mln ALL)	k = C/D	k* = k−k₀	Illegal Currency (Mln ALL)	v	NOE (Mln ALL)	NOE % GNP
2021	366,251	780,116	0.47	0.000	—	—	—	**n/a**
2022	387,652	841,969	0.46	0.000	—	—	—	**n/a**
2023	393,555	873,877	0.45	0.000	—	—	—	**n/a**
2024	423,556	913,107	0.46	0.000	—	—	—	**n/a**

During **the first phase (2006–2012)**, the C/D ratio fluctuates within a relatively stable band (0.99–1.39), consistent with the methodological requirement of a structurally constant k_0. This phase encompasses the global financial crisis of 2008–2009, which produced the highest observed C/D ratio (k = 1.39 in 2009), reflecting an intensification of cash-based informal transactions during the recession period. The gradual decline from 2009 to 2012 is consistent with economic recovery.

During **the second phase (2013–2024)**, the C/D ratio declines sharply and continuously, from 0.96 in 2013 to a minimum of 0.45 in 2023. This decline is not consistent with a genuine formalization of the economy, as independent estimates from the IMF, World Bank, and Schneider (2023) continue to place Albania's NOE at 28–35% of GDP during this period.

Table 3. Gutmann Approach — NOE Estimation for Albania, 2006–2024 (Mln ALL)

Note: *k_0 = 0.99 (base year 2007).*

Source: *Bank of Albania; INSTAT. Author's calculations*

4.2. NOE Estimates for the Valid Period (2006–2012)

For the methodologically valid period 2006–2012, the Gutmann method produces NOE estimates ranging from 4.7% to 16.8% of GNP. The trajectory reflects recognizable macroeconomic dynamics:

- **2006–2007:** NOE at approximately 7.8% of GNP, reflecting a period of moderate informal activity during economic growth.
- **2008–2009:** NOE peaks at 13.2% and 16.8% respectively, consistent with the well-documented countercyclical behavior of informal economies during recessions (Schneider, 2012). The sharp increase in cash holdings during the crisis period is a classic signal of heightened NOE.
- **2010–2012:** A gradual decline, consistent with economic stabilization and partial recovery of formal sector activity.

These estimates are below the 30–35% levels suggested by MIMIC-based studies (Schneider et al., 2020). This systematic underestimation is a known characteristic of the Gutmann method and is attributable primarily to the assumption of equal velocity (v) across sectors. If, as Feige (1979) argues, the NOE exhibits a higher velocity of money, the actual NOE would be proportionally larger. The Gutmann estimates should therefore be interpreted as conservative lower bounds for the Albanian NOE during this period. It produces reliable results only when the currency in circulation-to-deposit ratio (C/D) is structurally stable.

4.3. Structural Break after 2013: Why the Method Fails

The application of the Gutmann method beyond 2013 produces NOE estimates approaching zero, a result that is empirically untenable. Table 4 documents the structural causes of the C/D decline in the post-2013 period, distinguishing them from genuine informality reduction.

Table 4. Causes of C/D Decline in Albania, 2013–2024

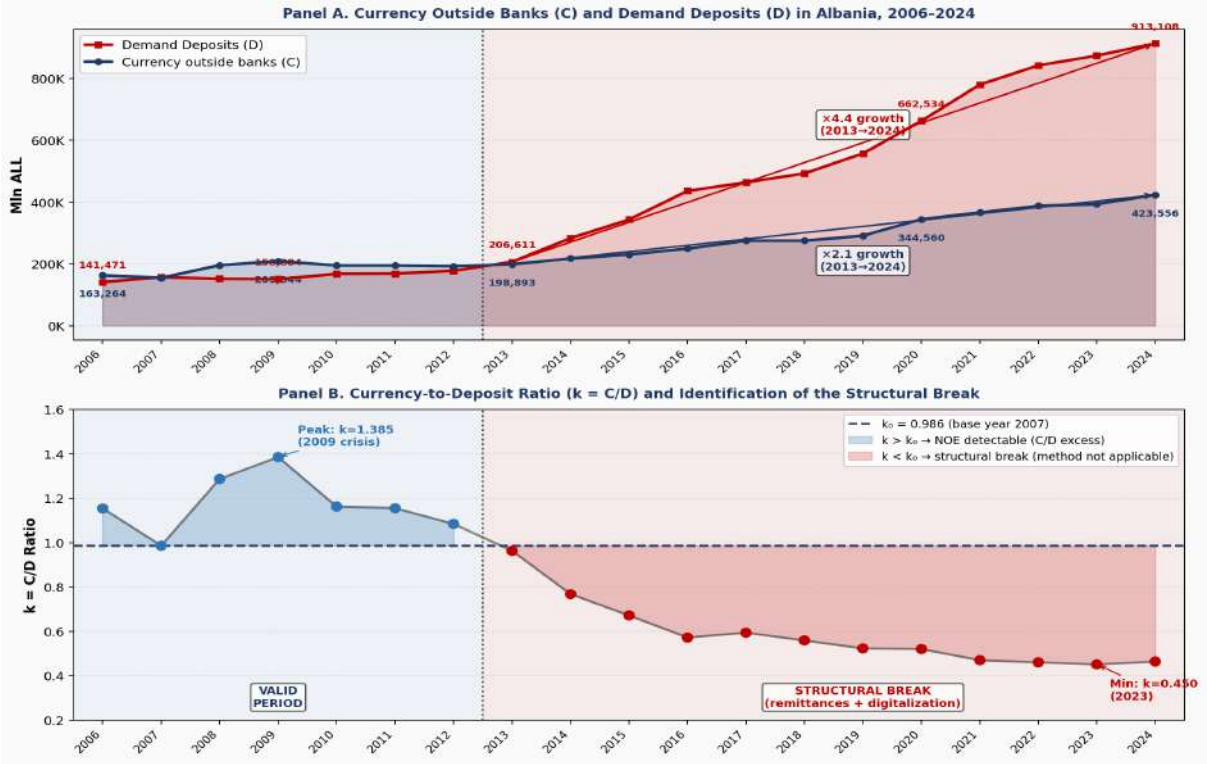
Year	D (Mln ALL)	C (Mln ALL)	k = C/D	Cause of C/D Decline (Non-NOE Factor)
2013	206,611	198,892	0.96	Beginning of decline – D increases driven by remittance inflows
2015	343,424	230,601	0.66	Tourism boom + emigrant deposits surge
2016	436,146	249,415	0.57	Payment digitalization – POS terminals & bank cards expand
2018	492,669	275,285	0.56	Internet banking widely adopted across the population
2020	662,534	344,560	0.52	COVID-19: precautionary savings rise, electronic payments accelerate
2022	841,970	387,651	0.46	High inflation – bank deposits used as store of value
2023	873,778	398,721	0.45	Record tourism revenues + Euro deposits channeled into banking system
2024	913,108	423,556	0.46	Fiscal digitalization (fiscalization reform) – cash displaced by electronic invoicing

Source: *Bank of Albania. Author's compilation*

The data in Table 4 and Figure 2 reveal a fundamental asymmetry: between 2013 and 2024, demand deposits (D) grew 4.42 times (from ALL 206,611 Mln to ALL 913,108 Mln), while currency outside the banking system (C) grew only 2.13 times (from ALL 198,892 Mln to ALL 423,556 Mln). This divergence is primarily driven by three non-NOE factors. **First,** the large-scale inflow of remittances from the Albanian diaspora, predominantly in Euro, has been

systematically deposited in the banking system, inflating demand deposits without a proportional increase in domestic cash circulation. Albania ranks among the top recipients of remittances relative to GDP in the Western Balkans (World Bank, 2023), making this a dominant structural factor. **Second,** the rapid expansion of tourism revenues after 2015 generated substantial foreign currency inflows that were channeled primarily through formal banking institutions, further increasing D. **Third,** the progressive digitalization of payment systems, including the introduction of POS terminals, internet banking, and more recently the mandatory fiscalization reform, has systematically displaced currency in circulation from formal sector transactions, reducing C independently of any change in NOE.

Figure 2. Currency Outside Banks (C), Demand Deposits (D), and the C/D Ratio, 2006–2024.



Panel A shows absolute levels; Panel B shows the C/D ratio relative to the base-year threshold

Source: *Bank of Albania; INSTAT. Author's calculations*

These findings are consistent with the theoretical critique advanced by Porter and Weinbach (1999) and Spiro (1994), who documented that changes in financial technology distort the C/D ratio in ways unrelated to the NOE. In the Albanian context, this distortion is amplified by the structural openness of the economy to remittance flows — a factor not present in the original US context for which the Gutmann method was designed.

5. DISCUSSION

5.1 Methodological Implications and Cross-validation

The findings of this study yield three methodological insights with relevance beyond the Albanian case.

First, the Gutmann method requires explicit pre-testing of C/D stability before application. In contexts where the banking system is expanding rapidly, remittances are significant, or payment digitalization is accelerating, the C/D ratio will exhibit a structural downward trend unrelated to informality. Applying the method without this diagnostic step will systematically underestimate the NOE in later periods, as demonstrated by the Albanian post-2013 experience.

Second, the choice of base year is decisive and should be grounded in structural economic criteria rather than statistical minimization alone. The minimum C/D ratio is not necessarily the appropriate baseline: if the minimum occurs during a period of digital payment expansion (as in Albania, 2023), its use as k_0 will mechanically suppress all earlier-period NOE estimates. A structurally stable intermediate period, one preceding major financial system transformations, provides a more theoretically defensible baseline.

Third, the estimates produced by the Gutmann method for the valid period (2006–2012) are best interpreted as conservative lower bounds, given the equal-velocity assumption. Cross-validation with independent estimates from Schneider (2023) and IMF (2018), which place Albanian NOE at 30–35% of GDP, confirms that the Gutmann method captures the directional dynamics of the NOE (peak at crisis, gradual recovery) but underestimates its absolute magnitude by approximately 15–20 percentage points. Future research applying the Currency Demand Approach (Tanzi, 1983) or MIMIC methodology could provide more precise estimates by relaxing the restrictive assumptions of the Gutmann approach.

5.2. Implications for Future Measurement in Albania

The structural limitations identified in this study have direct implications for the design of future measurement frameworks. Three methodological directions are recommended for the Albanian context.

1- Currency Demand Approach (CDA) developed by Tanzi (1983) offers a natural extension of the Gutmann method that overcomes its most critical limitation: the assumption of a fixed C/D baseline. The CDA estimates a currency demand function in

which cash holdings are explained by legitimate economic variables, income, interest rates, and the degree of financial development, while the residual demand attributable to the tax burden is interpreted as the NOE-related component. For Albania, this approach would explicitly model the structural increase in demand deposits driven by remittances and digitalization, thereby isolating the genuine informality signal from financial development noise.

2- Multiple Indicators Multiple Causes (MIMIC) model, which has produced the most widely cited global estimates of the NOE (Schneider et al., 2010; Medina & Schneider, 2018), would provide a more comprehensive assessment by combining monetary indicators with non-monetary proxies such as electricity consumption, employment in the informal sector, and tax revenue as a share of GDP. Given the availability of these data for Albania through INSTAT and Eurostat, a MIMIC application covering the full 2006-2024 period represents a feasible and high-priority research objective.
3- a hybrid approach, applying the Gutmann approach for the 2006-2012 period (where its assumptions are satisfied) and the CDA or MIMIC for 2013-2024, would yield a methodologically consistent time series covering the full period of analysis.

6. POLICY IMPLICATIONS AND STRATEGIC RECOMMENDATIONS

6.1 Policy Implications of the Non-Observed Economy

This section synthesizes the main policy implications derived from the analysis of the NOE using monetary aggregates. The findings indicate that the NOE is not merely a peripheral phenomenon, but rather a structural component of the economy that requires coordinated interventions at the fiscal, monetary, and institutional levels.

First, policymakers should move beyond merely acknowledging the existence of the NOE toward systematically integrating its estimates into strategic planning processes. According to Schneider (2015), transition economies often underestimate the size of the shadow economy, leading to suboptimal macroeconomic policy decisions. A well-designed regulatory framework should aim not only at enforcement but also at incentivizing formalization by reducing compliance costs. Tax system reforms should focus on broadening the tax base while lowering the tax burden on labor, thereby creating an environment where formal economic activity becomes more attractive than informality (Schneider, 2015; OECD, 2017).

Partial recognition of the NOE enables governments to increase revenue collection without necessarily raising tax rates. Bejaković (2017) emphasizes that adapting control mechanisms to

sectors that intensively use cash is essential for reducing the tax gap. In particular, consumption taxes such as VAT remain highly vulnerable to evasion; therefore, strengthening monitoring mechanisms at the final transaction stage is a critical priority. The digitalization of invoicing systems and the promotion of electronic payments represent key instruments in this regard (Bejaković, 2017; OECD, 2017).

The use of monetary aggregates to estimate the NOE provides a methodological advantage in capturing liquidity circulating outside formal banking channels. Enhancing the scope and quality of observable activities would improve the transparency and international comparability of this approach. Medina and Schneider (2018) suggest that the Currency Demand Approach (CDA) should be complemented with additional indicators, such as electricity consumption, to produce a more comprehensive assessment. Moreover, cross-border data aggregation is increasingly important in a globalized economy where hidden transactions often transcend national boundaries (Medina & Schneider, 2018).

The NOE poses risks that extend beyond public finances, undermining fair competition and social stability. In regions where informality is dominated by micro and small enterprises, purely repressive measures may lead to increased unemployment. Therefore, a stakeholder-inclusive approach is recommended (Williams, 2016; OECD, 2020).

Table 5: Key stakeholders and their Role in addressing the Non-Observed Economy

Stakeholder	Role in addressing the Non-Observed Economy (NOE)
Trade Unions	Identification of informal work and protection of workers' rights
Private Sector	Voluntary reporting, digitalization of transactions, promotion of fair competition
Civil Society	Monitoring, accountability, and pressure for transparency
Financial Institutions	Provision of data on monetary flows and detection of suspicious transactions
Academia	Development of new measurement methodologies

Source: *Adapted from OECD (2020); Williams (2016); Medina & Schneider (2018)*

6.2 Strategic Policy Recommendations

To consolidate progress in the formalization of the economy and address the remaining challenges associated with the NOE, a comprehensive and coordinated policy approach is required. A key priority is the further reduction of the ceiling for cash transactions, particularly in business-to-business and business-to-consumer transactions. Limiting the use of cash would incentivize the shift toward formal financial channels, thereby increasing transparency and traceability in economic activity. However, the effectiveness of such a measure depends on parallel efforts to strengthen electronic payment infrastructure and to raise public awareness regarding the benefits of formal transactions.

In this context, the introduction of incentives for electronic payments represents a complementary strategy. Encouraging consumers to use bank cards and digital platforms through mechanisms such as partial VAT refunds, fiscal lotteries, or other financial benefits can significantly influence behavioral change. By increasing the demand for traceable transactions, these measures contribute directly to reducing informality, particularly in sectors where cash usage remains prevalent.

At the same time, the continued improvement and expansion of the fiscalization system is essential. Addressing existing implementation gaps and extending monitoring to business-to-consumer transactions—especially in high-risk sectors such as tourism, services, and retail trade—would strengthen compliance. Equally important is enhancing the analytical capacity of tax authorities to effectively utilize fiscal data in identifying irregularities and enforcing compliance.

Reforms in the social security system and labor market policies also play a crucial role in addressing informality. Reducing the fiscal burden on wages and introducing incentives for businesses to declare actual salaries can encourage formal employment relationships. Such measures should be accompanied by stronger labor inspections to combat undeclared work. A more formalized labor market not only improves worker protection but also contributes to the sustainability of public finances through increased contributions to pension and healthcare systems.

Furthermore, financial education and public awareness are fundamental components of any long-term strategy. National campaigns aimed at informing citizens and businesses about the costs associated with informality and the benefits of operating within the formal economy can foster a culture of compliance. Promoting practices such as requesting fiscal receipts and using banking services helps build a more transparent and accountable economic environment.

Finally, strengthening regional and international cooperation is essential in the fight against the non-observed economy. Given the cross-border nature of many informal activities,

collaboration with neighboring countries and European Union institutions can facilitate the exchange of best practices, improve tax information sharing, and enhance policy coordination. In addition, leveraging the expertise of international organizations such as the IMF, the World Bank, and Eurostat can support the development of more robust measurement methodologies and more effective policy responses.

7. CONCLUSIONS

This study has applied the Gutmann Simple Currency Ratio method to estimate the non-observed economy in Albania for the period 2006–2024, using official data from the Bank of Albania and INSTAT. The analysis produces two distinct sets of findings — an empirical assessment for the methodologically valid period, and a structural diagnosis of why the method yields unreliable results in the post-2013 context.

For the period 2006–2012, the Gutmann method yields NOE estimates ranging from 7.8% to 16.8% of GNP. The trajectory is consistent with macroeconomic dynamics: NOE peaks during the 2008–2009 global financial crisis (16.8% in 2009) and declines gradually during the recovery phase (2010–2012). While these estimates are conservative lower bounds relative to independent cross-national estimates (30–35% of GDP), the directional dynamics are robust and provide meaningful insights into the evolution of informal activity during this period.

For the post-2013 period, the method produces NOE estimates approaching zero — a result that is empirically untenable. This study identifies the structural causes of this failure: demand deposits grew 4.42 times between 2013 and 2024 (driven by remittances, tourism revenues, and banking system expansion), while currency grew only 2.13 times. This asymmetric growth depresses the C/D ratio structurally, independently of any genuine formalization of the economy. This finding constitutes the primary original contribution of the study: a documented identification of the conditions under which the Gutmann method loses its inferential validity in transition economies with high remittance inflows.

Two conclusions emerge for research and policy:

For researchers: The Gutmann method should be preceded by a structural stability test of the C/D ratio. In economies with rapid banking expansion or significant remittance inflows, the method is applicable only in the pre-distortion period. The Currency Demand Approach (Tanzi, 1983) or MIMIC models offer more appropriate alternatives for the post-2013 Albanian context.

For policymakers: The apparent decline in the C/D ratio after 2013 should not be interpreted as evidence of economic formalization. Independent estimates consistently place Albania's

NOE above 28–30% of GDP, underscoring the need for sustained and multi-dimensional policies to address informality.

Future research should extend this analysis by applying the Tanzi (1983) Currency Demand Approach, which explicitly controls for structural determinants of money demand, and by integrating non-monetary indicators such as electricity consumption and employment surveys to produce a more comprehensive picture of Albania's non-observed economy.

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CAPITAL BUDGETING IMPACT ON FINANCING GINGER AND GROUDNUTS SEEDLINGS PRODUCTION ON THE NIGERIAN ECONOMIC GROWTH

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ABSTRACT

This research work has so far examined the impact of capital budgeting on ground nut and ginger production seedlings on Nigeria's economic growth. Ex-post facto research design was adopted employing Unit root test and ARDL approach. Specific references were made to the relevant macroeconomic variables complementary to financing groundnut and ginger. Empirical results reveal that financing to groundnut and ginger production considered for the analysis had insignificant effect on economic growth in Nigeria during the period under review, implying that financing is an important determinant of groundnut and ginger production productivity in Nigeria. The real Gross Domestic Product is the dependent variable proxied economic growth. The result shows that 1 percent increase in financing groundnut and ginger production leads to about 0.004% increase in real gross domestic product (RGDP). It was found that coefficient of FGGP is positive, indicating positive relationship between FGGP and RGDP in the periods 2002-2025, and this is in line with a priori. This result is statistically insignificant at 5 percent as the p-value of 0.4909. The standard error measures the statistical reliability of the coefficient estimates- the larger the error, the more statistical noise in the estimates. The standard error is 0.005908 percent which is small or significant and thus shows that FGGP is statistically reliable to predict RGDP in Nigeria. The study therefore recommended that, government should provide financing policies in place in terms of financing groundnut and ginger production that will boast the agricultural sector output to cushion effects of high cost of living in the country.

Keywords: Capital Budgeting, Agricultural Financing, Ginger Production, Groundnut Production, Economic Growth.

1.0 Introduction

1.1 Background to the Study

Capital budgeting refers to the firm decision of an organizations management to invest in any enterprise of their choosing, in this case groundnut and ginger seedlings production. It also refers to the process of organizing, coordinating and managing a firm's resources effectively.

Ginger (Zingiber officinale) is a rhizome, which consist of numerous short finger-like structures or branches born horizontally near the surface of the soil. Two commercial varieties are commonly cultivated in Jaba region. The yellow ginger variety locally called "Tafin Giwa" with a bold yellow rhizome flesh is stout with short internodes. The black ginger variety locally called "Yatsun Biri" with a dull-grey colour rhizome. The yellow variety is more popular than the black variety apparently due to its high yielding capacity and pungency (Kure, 2007). Ginger is produced in several parts of Nigeria particularly in the Guinea Savanna Zone (southern part of Kaduna State) and to a little extent in Keffi and Akwanga Local Government Areas of Nasarawa State (Dauda and Waziri, 2006). Ginger is most widely grown by all farming communities in the Jaba region. Indeed, it is the main cash crop that all small holder farmers in the region are willing and deeply involved in cultivating due to high profit. This made some farmers in the area to devote all their farmlands to ginger production as against subsistence crops such as guinea corn or maize. In terms of local consumption, however, it is the least among all the other cultivars. This is because; over 95% of its produce is exported to various countries of the world as export commodity. Owing to the above outstanding and astonishing qualities of ginger production and its economy, one may expect its farming practice to be simple; just like that of the other crops grown in the area or elsewhere. But on the contrary, it requires special skills, know-how and finance. Poor, inadequate or no access to finance on the part of the Ginger farmers has been a long-time problem affecting their productivity.

Groundnut (Arachis hypogaea L.) belongs to the genius Arachis in family legiminosea (Fabacaea), which has replaced the traditional Bambara groundnut (VignaSubterranean) in many areas of the country. Groundnut seeds or nuts are a nutritional source of vitamin E, Niacin, Folacin, calcium, phosphorous, magnesium, zinc, iron, riboflavin, amino and potassium (Girei et al., 2013). Groundnut, sometimes called Peanut, is majorly grown for its nut, oil or stem. Groundnut cake is often deep-fried or dried to make a Kuli-Kuli snack (Hamidu et al., 2006). Similarly, Groundnut haulms also provide excellent hay for livestock, while its flour is also used as an ingredient in soup, confectionaries and pudding (Taru et al., 2010). Groundnut is the

13th most important food crop in the world. It is the world's 4th most important source of edible oil and third most important source of vegetable protein (Taru et al., 2010). It contains 48-50% oil, 26-28% protein and 11-27% carbohydrates, minerals and vitamins (Muktar, 2009). It is grown on 26.4 million ha worldwide with a total production of 36.1 million metric tons and an average productivity of 1.4 metric tons/ha. The crop is grown in nearly 100 countries, and the leading producer of the crop are China, India, Nigeria, the U.S.A, Senegal, Indonesia and Sudan (FAO, 2009). In the early 1900s, Nigeria was one of the major exporting countries, with Kano as the major producing area (and was ranked the 4th in groundnut production globally. Due to the crop's massive production, it was usually stacked in pyramid-like structures made from numerous groundnut sacks. It was then viewed as a tourist attraction and a symbol of wealth. During the 1900s, when Nigeria was among the top producers of groundnuts in the world and the largest producer in Africa, the cash crop was very yielding, as it was largely exported to other countries owing to its health benefits and numerous purposes. After that, however, groundnut and other cash crop production declined due to the shift from agriculture to oil. Although, recently, with the help of the government to revive agriculture at its best through the provision of farm equipment and supplies, fertilizers and related others, most of the cash crop productions are now becoming yielding (International Crops Research Institute for the Semi-Arid Tropic [ICRISAT], 2015). In Nigeria, groundnut is produced in almost all the northern states, including the study area. The leading producing states include Niger, Kano, Sokoto, Katsina, Kaduna, Adamawa, Yobe, Plateau, Borno, Taraba, Gombe and Nassarawa. Groundnut is a major source of edible oil and livelihoods for small-scale farmers in Northern Nigeria. Being a labour-intensive crop, it generates employment for the rural poor. It is planted on about 34% 2 of the total cultivated area and contributes 23% of household cash revenue (ICRISAT, 2015). However, despite the importance of groundnut, there is still the insufficiency of the crop due to some problems that hinder its productivity. This problem is attributed to rapid urbanization, low per capita income, poor storage, inadequate transportation and marketing facilities, and a non-chalant attitude to agriculture. As a result, small Nigerian agricultural operators face pure competition at the production and marketing stages. Similarly, crop productivity or yield is a function of environment, plant, management and socio-economic factors and their interactions; and maximum yield in a given environment is possible only when all these factors are at optimum levels (Nandi et al., 2010**).**

2.0 LITERATURE REVIEW

On the Input and Output relationship, Audu et al. (2017) cited in Hajara Adamu etal (2023) reported that a percentage increase in production inputs would lead to a percentage increase in output with all things being equal. At the same time, Amaza et al. (2002) cited in Hajara Adamu etal (2023) added that a positive relationship exists between labour and farm gross margin. Ani et al. (2013) cited in Hajara Adamu etal (2023) further added that a percentage increase in pesticide use would bring about a proportionate increase in output. This was because of farmers' access to a maximum level of credit. Similarly, Reardon et al. (2007) revealed that fertiliser positively affected crop yield. While Schroeder et al. (2013) compared the yield, profit and labour inputs of farmers using certified seeds to those using recycled hybrid seeds in Kenya, and their results indicated significantly higher yields for farmers using certified breeds but lower productivity due to more intensive use of labour in fertiliser application in certified hybrid seeds farming system. The major problems affecting groundnut production include a lack of capital, and improved seeds (Ani et al., 2013 & Abubakari et al., 2019), while Audu et al. (2017) and Alabi et al. (2013) both cited in Hajara Adamu et al (2023) reported a lack of extension services and fertiliser. So therefore, the objective of this study is to determine the extent at which finance impact on the production of groundnut and Ginger and hence economic growth in Nigeria.

3.0 Research Methodology

3.1 Research Design

The research design adopted is the ex-post facto research design. This design method was chosen because; it implies a systematic process where the researcher cannot just manipulate data due to its occurrence.

3.2 Data Sources and Collection

The time series Secondary data running from 2000 - 2023 extracted from the Central Bank of Nigeria Statistical Bulletin and National Bureau of Statistics annual bulletins were the sources of data used for this study.

3.3 Technique for Data Analysis

Econometric software (E-Views version 9.0) was used to analyze the data collected. The descriptive statistics for all study variables were extracted from the E-views 9.0 outputs and were presented in Tables. Also, the employed was the Augmented Dickey-Fuller Test to test for stationarity and the Ordinary Least Square for regression.

3.4 Model Specification

The model proxies RGDP as the dependent variable (endogenous variable) that measures

economic growth while Loans/advances and interest rates represent the independent

variables (exogenous variables).

The econometric form of the model is hereby specified as;

RGDP = f(LA, INTR)

The econometric equation becomes;

Regression of RGDP = $\alpha+\beta_1 FGGP+U_t$

Where;

α = Intercept of relationship in the model

β_1 = Coefficient of the independent variable LA (FGGP)

3.5 A Priori Expectations

This defines the theoretical expectations of the signs of the parameters of the model. These

are mathematically expressed as follow;

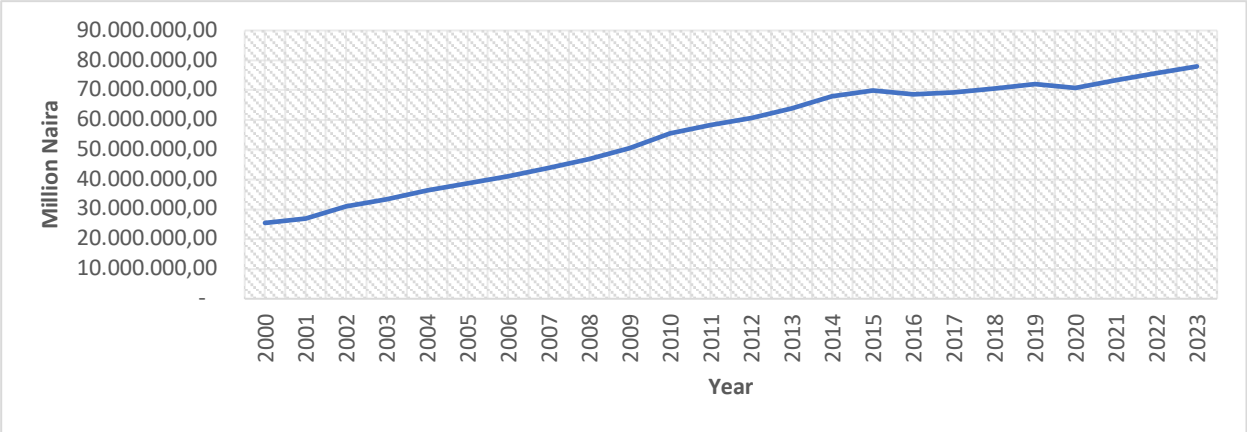
$\beta_1 > 0$ = Positive relationship between LA (FGGP) and RGDP

4.0 Data Presentation, Discussion and Findings

4.1: Trend Analysis

The trends in the variables are captured in separate figures below. This is to give an insight into the existence of any unique characterization of the variables over the study

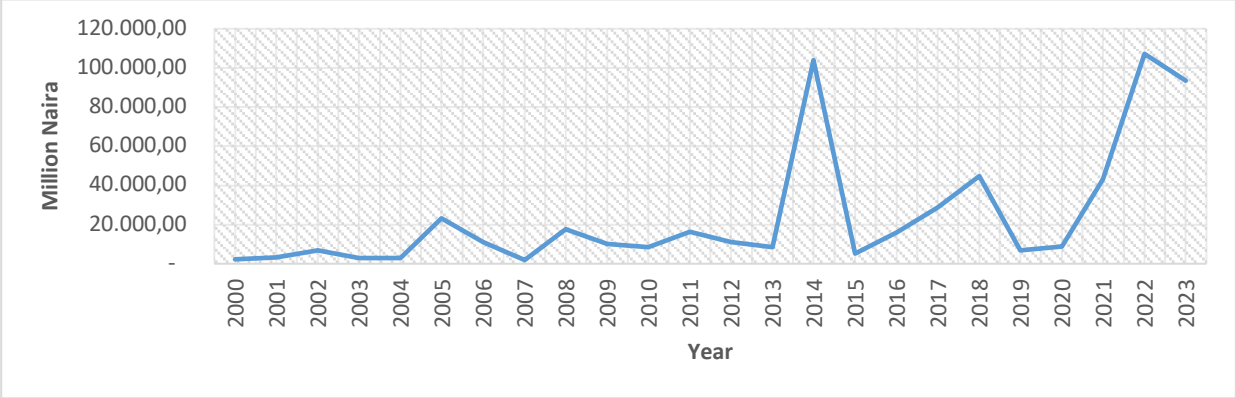
Figure 4.1.1: A line chart showing the distribution of trends of Nigeria's real Gross Domestic Product Growth rate (%) from 2000 -2023



Source: Author's computation, 2025 using E-views 9.0

Examining Fig. 4.1.1 above showed that the Gross Domestic Growth rate (GGR) is an upward trend. The figure also reveals that GDP is generally not stable during the period 2000-2023. The time series data in Appendix 1 underscores the trends in RGDP from 2000 -2023 This indicates that RGDP has been up and down trends (see Appendix 1 attached).

Figure 4.1.2: A line chart showing the distribution of trends of Nigeria's Financing groundnut/ginger Production (=N=Million) from 2000-2023



Source: Author's computation, 2024 using E-views 9.0

Fig. 4.1.2 above showed that the groundnut/ginger Production from 2000 to 2023. The Financing to groundnut/ginger was flattering from 2000 to 2004 then zig from 2005 to 2020 and sharply rise in 2021 to 2023. The figure shows that Financing to groundnut/ginger production in Nigeria was not stable between 2007 and 2016 while stable from 2017 to 2023. The initial instability in Loans and Advances experienced in Nigeria could be due to government policies inconsistencies.

Table 4.1.3: Summary of Descriptive Statistics

Variable	Mean	Std	Max	Min	Skewness	Jarque-Bera	Probability
RGDP	7.72	7.89	7.41	0.15	- 0.68	2.60	0.27
FPOP	4.09	5.03	3.27	0.52	0.33	0.94	0.62

Source: Author's computation, 2025 using E-views 9.0

The table 4.1.3 reveals that real Gross domestic product growth (RGDP) has a mean of 7.72 and varies from a minimum of 7.41 to a maximum of 7.89 and a standard deviation of 7.77 with a probability value of 2.60 while groundnut/ginger Production (FGGP) has a mean of 4.75 and varies from a minimum of 3.03 to a maximum of 5.53 and a standard deviation of 5.07 with a probability value of 3.01 RGDP and FGGP are were positively skewed.

4.3 Results of Tests Conducted

The results of tests conducted are summarized, presented in tabular form and analyzed below: The tests conducted are: unit root, and autoregressive distributive lag (ARDL) Model.

4.3.1 Unit Root Test

Dickey-Fuller (1979) stated that there is likelihood of obtaining spurious results if the series that generated the results are non-stationary. This is why this study investigated the time series properties of the data by conducting unit root test for stationarity using Augmented Dickey-Fuller (ADF) method. The results are presented on table 4.2.3 below.

Table 4.2.2: Summary of the description of variables and their corresponding unit and sources

Variable	Description	Unit	Source
RGDP	Real Gross Domestic Growth	Percentage	NBS
FGGP	Financing to Groundnut/Ginger Production	Million Naira	CBN

Source: Researcher's own computation

Table 4.2.3: Augmented Dickey-Fuller (ADF) Unit Root Test

Variable	ADF Test Statistics at Level	ADF Test Statistics at First Difference	5% Critical Value at Level	5% Critical Value at First Difference	Probability Value at Level	Probability Value at First Difference	Order of Cointegration
INRGDP	-4.854	-2.580	-2.998	-3.005	0.008*	0.1120	1(0)
INFGGP	-3.196	-3.679	-2.998	-3.040	0.033	0.014*	1(1)

Source: Author's computation, 2023 using E-views 9.0

The results of unit root test shown on table 4.2.3 above revealed that all the absolute values of ADF test statistics for RGDP and FGGP are greater that their critical values at 5% implying that RGDP and FGGP are stationary at 5%, It is integrated of order 1, and 0 that is, I(0) and 1(1) indicating mixed result. The results also showed that all the variables are stationary at both 5% since their absolute value of ADF statistics are respectively greater than their critical values at 5%.

Table 4.2.4: Regression of $RGDP=\alpha+\beta_1 FGGP+U_t$

Dependent Variable: RGDP

Method: ARDL

Date: 01/15/25 Time: 06:26

Sample (adjusted): 2001 2023

Included observations: 23 after adjustments

Maximum dependent lags: 4 (Automatic selection)

Model selection method: Akaike info criterion (AIC)

Dynamic regressors (4 lags, automatic): GGP

Fixed regressors: C

Number of models evalulated: 20

Selected Model: ARDL(1, 0)

Note: final equation sample is larger than selection sample

Variable	Coefficient	Std. Error	t-Statistic	Prob.*

RGDP(-1)	0.917958	0.019504	47.06480	0.0000
GGP	0.004145	0.005908	0.701713	0.4909
C	0.636476	0.136759	4.654010	0.0002

		Mean dependent var	7.732609
R-squared	0.994541		
Adjusted R-squared	0.993995	S.D. dependent var	0.140881
		Akaike info criterion	-6.075904
S.E. of regression	0.010917		
Sum squared resid	0.002384	Schwarz criterion	-5.927796
		Hannan-Quinn criter.	-6.038655
Log likelihood	72.87289		
F-statistic	1821.889	Durbin-Watson stat	2.063053
Prob(F-statistic)	0.000000		

*Note: p-values and any subsequent tests do not account for model selection.

Source: Output of E-Views 9.0, 2025.

Model:

RGDP = 0.686+0.004FGGP+ $\mathbf{U_t}$

(4.654) (0.701)

Where;

RGDP = Real Gross Domestic Product = Dependent Variable

FGGP = Financing to Groundnut/Ginger Production = Independent Variable

4.3 Discussion of Results

The result on table 4.2.4 above revealed the following:

The equation shows that $\alpha = 0.686$ which is the intercept. This is the base level of prediction for the dependent variable when all the independent variables are equal to zero. The

coefficients of the independent variables measure how a percentage change in independent variables affect the dependent variable.

(i.) 1 percent increase in financing groundnut and ginger production leads to about 0.004% increase in real gross domestic product (RGDP). It was found that coefficient of FGGP is positive, indicating positive relationship between FGGP and RGDP in the periods 2000-2023, and this is in line with a priori. This result is statistically insignificant at 5 percent as the p-value of 0.4909. The standard error measures the statistical reliability of the coefficient estimates- the larger the error, the more statistical noise in the estimates. The standard error is 0.005908 percent which is small or significant and thus shows that FGGP is statistically reliable to predict RGDP in Nigeria.

4.4. Discussion of Findings

Based on the quest to examine the impact of financing of agricultural sector on real gross domestic product in Nigeria, the ARDL result revealed that components of financing such as; loans and advances had a symmetric impact on RGDP growth rate in Nigeria. This is because the positive changes in financing to groundnut and ginger production had effect on RGDP growth rate in Nigeria. This implied that the increase in financing to groundnut and ginger production will had more positive impact on RGDP in the Nigerian economy within the study period.

5.0 Conclusion and Recommendations

This research study has so far examined the effects of financing on economic growth in Nigeria employing Unit root test and ARDL approach. Specific references were made to the relevant macroeconomic variables complementary to financing groundnut and ginger. Empirical results reveal that financing to groundnut and ginger production considered for the analysis had insignificant effect on economic growth in Nigeria during the period under review, implying that financing is an important determinant of groundnut and ginger production productivity in Nigeria. The real Gross Domestic Product is the dependent variable proxied economic growth. The result shows that there is positive and significant impact of financing groundnut and ginger production The study therefore recommended that, government should provide financing policies in place in terms of financing groundnut and ginger production that will boast the agricultural sector output to cushion effects of high cost of living in the country.

Appendix 1: Original Data Sourced (=N= Million)

Year	Real GDP (=N= Million)	Groundnut/Ginger (=N= Million)
2000	25,430,423.39	2,123.00
2001	26,935,315.65	3,192.50
2002	31,064,272.13	6,826.90
2003	33,346,624.77	3,030.00
2004	36,431,373.71	3,025.00
2005	38,777,013.73	23,160.00
2006	41,126,678.97	11,080.00
2007	43,837,391.99	1,866.00
2008	46,802,760.44	17,465.00
2009	50,564,263.25	10,240.00
2010	55,469,350.31	8,440.00
2011	58,180,351.90	16,324.92
2012	60,670,050.46	10,985.00
2013	63,942,845.56	8,350.00
2014	67,977,459.22	103,820.00
2015	69,780,692.72	5,030.00
2016	68,652,430.36	15,955.00
2017	69,205,691.11	28,640.00
2018	70,536,348.62	44,740.00
2019	72,094,094.00	6,720.00
2020	70,800,543.49	8,840.00
2021	73,382,771.39	43,155.00
2022	75,768,945.32	107,195.00
2023	77,936,100.05	93,389.00
2024	76,396,121.06	87.376.00

Source: Source: National Bureau of Statistics and Central Bank of Nigeria's Bulletin, 2023

Appendix 2: Transformed Data

Year	Log of RGDP	Log of FGGP
2000	7.41	3.33
2001	7.43	3.50
2002	7.49	3.83
2003	7.52	3.48
2004	7.56	3.48
2005	7.59	4.36
2006	7.61	4.04
2007	7.64	3.27
2008	7.67	4.24
2009	7.70	4.01
2010	7.74	3.93
2011	7.76	4.21
2012	7.78	4.04
2013	7.81	3.92
2014	7.83	5.02
2015	7.84	3.70
2016	7.84	4.20
2017	7.84	4.46
2018	7.85	4.65
2019	7.86	3.83
2020	7.85	3.95
2021	7.87	4.64
2022	7.88	5.03
2023	7.89	4.97
2024	7.98	6.87
	7.86	5.94

Source: Researcher's own computation

Appendix 3: Null Hypothesis: **RGDP has a unit root**

Null Hypothesis: RGDP has a unit root

Exogenous: Constant

Lag Length: 0 (Automatic - based on SIC, maxlag=5)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-4.854200	0.0008
Test critical values:	1% level	-3.752946	
	5% level	-2.998064	
	10% level	-2.638752	

*MacKinnon (1996) one-sided p-values.

Augmented Dickey-Fuller Test Equation

Dependent Variable: D(RGDP)

Method: Least Squares

Date: 01/15/25 Time: 06:35

Sample (adjusted): 2001 2023

Included observations: 23 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
RGDP(-1)	-0.073597	0.015161	-4.854200	0.0001
C	0.588428	0.116943	5.031763	0.0001

R-squared	0.528760	Mean dependent var	0.020870
Adjusted R-squared	0.506320	S.D. dependent var	0.015348
S.E. of regression	0.010784	Akaike info criterion	-6.138538

			-6.039800
Sum squared resid	0.002442	Schwarz criterion	
			-6.113706
		Hannan-Quinn criter.	
Log likelihood	72.59319		
		Durbin-Watson stat	2.034861
F-statistic	23.56326		
Prob(F-statistic)	0.000085		

Appendix 4: Null Hypothesis: D(FGGP) has a unit root

Null Hypothesis: D(GGP) has a unit root

Exogenous: Constant

Lag Length: 4 (Automatic - based on SIC, maxlag=5)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-3.678546	0.0143
Test critical values:	1% level	-3.857386	
	5% level	-3.040391	
	10% level	-2.660551	

*MacKinnon (1996) one-sided p-values.

Warning: Probabilities and critical values calculated for 20 observations

and may not be accurate for a sample size of 18

Augmented Dickey-Fuller Test Equation

Dependent Variable: D(GGP,2)

Method: Least Squares

Date: 01/15/25 Time: 06:36

Sample (adjusted): 2006 2023

Included observations: 18 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(GGP(-1))	-7.722897	2.099443	-3.678546	0.0032
D(GGP(-1),2)	5.427411	1.889248	2.872788	0.0140
D(GGP(-2),2)	3.650813	1.445451	2.525725	0.0266
D(GGP(-3),2)	1.879214	0.850309	2.210038	0.0473
D(GGP(-4),2)	0.616833	0.333802	1.847900	0.0894
C	0.340125	0.129142	2.633727	0.0218

		Mean dependent var	-0.052222
R-squared	0.892363		
Adjusted R-squared	0.847515	S.D. dependent var	1.075363
		Akaike info criterion	1.363708
S.E. of regression	0.419922		
		Schwarz criterion	1.660498
Sum squared resid	2.116017		
		Hannan-Quinn criter.	1.404631
Log likelihood	-6.273369		
		Durbin-Watson stat	1.865228
F-statistic	19.89726		
Prob(F-statistic)	0.000020		

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AĞRI BEKLENTİSİNİN MOTOR PERFORMANS VE REHABİLİTASYON SÜRECİ ÜZERİNE ETKİLERİ

THE EFFECTS OF PAIN EXPECTATION ON MOTOR PERFORMANCE AND THE REHABILITATION PROCESS

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ÖZET

Ağrı, yalnızca dokularda meydana gelen bir hasarın sonucu değil; bireyin geçmiş deneyimleri, inançları ve geleceğe dair beklentileri ile şekillenen karmaşık bir deneyimdir. Bu doğrultuda, rehabilitasyon sürecinde ağrıya ilişkin beklentiler, motor performans ve fonksiyonel hareketler üzerinde belirleyici bir rol oynayabilmektedir. Literatürde, olumsuz ağrı beklentisinin hareket sırasında tehdit algısını artırdığı belirtilmektedir. Artan tehdit algısı ile kaçınma davranışlarını tetikleyerek motor performansı olumsuz etkilediği bildirilmektedir. Bu durum, nocebo etkisi (olumsuz beklentilerin bireyde daha kötü sonuçlara yol açması) ve korku-kaçınma modeli çerçevesinde açıklanmaktadır. Öte yandan, olumlu beklentilerin ağrı algısını modüle edebildiği gibi performansı da destekleyebildiği gösterilmiştir. Placebo etkisi kapsamında değerlendirilen bu durum ise bireyin hareket sırasında daha yüksek güven algısı geliştirmesi ve hareketi daha etkin gerçekleştirmesi ile ilişkilendirilmektedir. Bu etkilerin bireyler arasında farklı düzeylerde ortaya çıkabileceği belirtilmektedir. Bu farklılıkların, bireysel psikososyal özellikler, önceki deneyimler ve çevresel faktörler ile etkileşim içinde şekillendiği vurgulanmaktadır. Ayrıca, beklentilerin zaman içerisinde değişebilir bir yapıya sahip olması da rehabilitasyon sürecinde sürekli değerlendirilmesini gerekli kılmaktadır. Dolayısıyla, beklenti mekanizmaları motor çıktı üzerinde dolaylı ancak anlamlı bir etkiye sahiptir. Bu bağlamda, rehabilitasyon süreci yalnızca fiziksel iyileşmeye odaklanan bir yaklaşım olarak düşünülmemelidir. Bireyin ağrıya ilişkin algı ve beklentilerinin de dikkate alındığı bütüncül bir biçimde ele alınmalıdır.

Anahtar Kelimeler: Ağrı beklentisi, motor performans, rehabilitasyon.

ABSTRACT

Pain is not merely a result of tissue damage; rather, it is a complex experience shaped by an individual's past experiences, beliefs, and expectations about the future. In this context, pain-related expectations may play a decisive role in motor performance and functional movements during the rehabilitation process. The literature indicates that negative pain expectations increase the perception of threat during movement. Increased threat perception, in turn, triggers avoidance behaviors and negatively affects motor performance. This phenomenon is explained within the framework of the nocebo effect (where negative expectations lead to worse outcomes) and the fear-avoidance model. On the other hand, positive expectations have been shown to modulate pain perception as well as support performance. This condition, evaluated within the scope of the placebo effect, is associated with the individual developing a higher sense of confidence during movement and performing movements more effectively. These effects may occur at different levels across individuals. These differences are emphasized to be shaped by the interaction of individual psychosocial characteristics, previous experiences, and environmental factors. In addition, the fact that expectations may change over time necessitates their continuous evaluation throughout the rehabilitation process. Therefore, expectation mechanisms have an indirect yet significant effect on motor output. In this context, the rehabilitation process should not be considered solely as an approach focused on physical recovery. It should be addressed within a holistic framework that also takes into account the individual's perceptions and expectations related to pain.

Keywords: Pain expectation, Motor performance, Rehabilitation.

GİRİŞ

Ağrı, yalnızca periferik dokulardan kaynaklanan basit bir biyolojik sinyal değildir. Duyusal ve duygusal bileşenlerin yanı sıra merkezi ve psikososyal süreçlerin etkileşimi ile şekillenen bir deneyimdir (1,2). Bu çerçevede, özellikle kronik ağrı olmak üzere, ağrı günümüzde biyopsikososyal model çerçevesinde ele alınmaktadır (3). Bireyin geçmiş deneyimleri ve bilişsel süreçleri, ağrının algılanması ve yorumlanmasında önemli bir rol oynamaktadır. Bu durum ağrı değerlendirmesini doğrudan etkilemektedir (4). Ağrının bilişsel ve duygusal süreçler tarafından modüle edilebilmesi, benzer uyaranların bireyler arasında farklı biçimlerde algılanmasına yol açabilmektedir (5). Bu bilişsel süreçler içerisinde beklenti, ağrı deneyimini şekillendiren temel unsurlardan biri olarak kabul edilmektedir (6). Bireyin gelecekte yaşayacağı bir duruma ilişkin öngörüleri hem ağrının şiddetini hem de bu ağrının nasıl yorumlanacağını belirleyebilir (7). Özellikle hareketle ilişkili ağrıya eşlik eden korku ve kaygı, bireyin davranışlarını ve hareketle kurduğu ilişkiyi önemli ölçüde etkileyebilmektedir (8).

Beklenti temelli bu modülasyon yalnızca ağrı algısını etkilemekle sınırlı değildir. Aynı zamanda bu deneyime eşlik eden bilişsel ve nörofizyolojik süreçleri de etkilediği giderek artan bir ilgiyle ele alınmaktadır (9). Rehabilitasyon bağlamında motor performans çok boyutlu bir yapıdır. Kas aktivasyonu, kuvvet üretimi, hareket kontrolü ve koordinasyon gibi bileşenleri içerir. Ayrıca fonksiyonel iyileşmenin temel belirleyicilerinden biridir. Bununla birlikte, motor performans ve motor öğrenme süreçlerinin yalnızca biyomekanik kapasite ile sınırlı olmadığı gösterilmiştir. Bu süreçlerin bilişsel süreçler ve ağrı ile ilişkili merkezi mekanizmalar tarafından da şekillendirilebileceği belirtilmektedir (10–11). Olumsuz beklentiler ve ağrıya ilişkin korkunun, hareketten kaçınma davranışları ve kinesiophobia ile ilişkili olduğu rapor edilmiştir (12, 13). Bu faktörlerin motor performans ve fonksiyonel çıktılar üzerinde olumsuz etkiler oluşturabildiği ortaya konmuştur. Buna karşılık, olumlu beklentilerin motor çıktıyı artırabildiği ve görev performansını iyileştirebildiği bildirilmektedir (14).

Bu etkilerin altında yatan mekanizmaların anlaşılmasında plasebo ve nocebo kavramları önemli bir yer tutmaktadır. Plasebo, pozitif beklentiler aracılığı ile ağrı algısını modüle eder. Nocebo ise negatif beklentiler yoluyla ağrı deneyimini artırarak bireylerin davranışsal ve fonksiyonel çıktıları üzerinde olumsuz etkiler oluşturabilmektedir (9). Bu süreçlerin, tahmine dayalı işleme (predictive processing) ve top-down modülasyon gibi merkezi sinir sistemi mekanizmaları aracılığıyla gerçekleştiği ileri sürülmektedir (15–16). Bu çerçeve, beklentinin sadece psikolojik bir değişken olmadığını gösterir. Aynı zamanda ölçülebilir nörofizyolojik süreçlerle ilişkili bir düzenleyici olduğunu ortaya koymaktadır.

Nörofizyolojik düzeyde, plasebo ve nocebo etkilerinin çeşitli nörotransmitter sistemleri aracılığıyla ortaya çıktığı bildirilmektedir. Bu sistemler arasında başta endojen opioid ve dopaminerjik sistemler yer almaktadır. Plasebo analjezisi sırasında bu sistemlerin aktive olduğu, nocebo etkilerinin ise karşıt mekanizmalarla ilişkili olarak geliştiği gösterilmiştir (17,18). Bu nörokimyasal ayrışma, plasebo ve nocebo etkilerinin ortak bir beklenti mekanizmasını paylaştığını göstermektedir. Bu etkilerin ise farklı mekanizmalar üzerinden işlediği anlaşılmaktadır. Bu durum, klinik müdahale stratejilerinin bu iki süreci ayrı ayrı hedeflemesi gerekebileceğini düşündürmektedir.

Tüm bu bulgular ile beklenti temelli bilişsel süreçlerin ağrı deneyimi üzerindeki etkisini ortaya koymaktadır. Aynı zamanda motor davranış üzerindeki rolü de vurgulanmaktadır. Ancak bu etkilerin motor performans üzerindeki spesifik yansımalarının henüz yeterince açıklığa kavuşturulamadığı anlaşılmaktadır. Özellikle rehabilitasyon bağlamında, beklentinin motor performans ve hareket kalitesi üzerindeki doğrudan etkilerini inceleyen çalışmalar sınırlıdır. Bu durum, bilişsel süreçler ile motor çıktılar arasındaki ilişkinin daha ayrıntılı biçimde ele alınmasını gerekli kılmaktadır. **Bu nedenle, mevcut çalışma beklenti temelli mekanizmaların motor performans üzerindeki etkilerini incelemeyi amaçlamaktadır. Ayrıca, bu ilişkinin altında yatan süreçleri daha iyi anlamayı ve alandaki bilgi boşluğunu doldurmayı hedeflemektedir.**

AĞRI BEKLENTİSİNİN MOTOR PERFORMANS VE REHABİLİTASYON SÜRECİNE ETKİLERİ

Ağrıya ilişkin beklentiler, motor performansı yalnızca davranışsal düzeyde değil, motor kontrolün altında yatan merkezi süreçler aracılığıyla da şekillendiren önemli bir belirleyicidir. Bu etki özellikle motor hazırlık sırasında kortikospinal uyarılabilirlikteki değişimlerle ilişkilidir (19). Bir hareketin ağrılı olacağına dair beklenti, hareket öncesi hazırlık aşamasında kas aktivasyon paternlerini değiştirir. Böylece daha koruyucu ve temkinli motor stratejilerin devreye girmesine neden olmaktadır (20). Dolayısı ile ortaya çıkan değişmiş kas aktivasyon paternleri, motor davranış ve çıktılar üzerinde doğrudan etkili olmaktadır (20,21). Söz konusu yanıtlar kısa vadede olası tehditten korunmayı amaçlayan adaptif süreçler olarak değerlendirilebilir. Ancak uzun vadede motor kontrolün bozulması ve fonksiyonel performansta azalma ile ilişkili olabilmektedir.

Hareketin yürütülmesinde duyusal ve motor süreçler arasındaki etkileşim, sensorimotor entegrasyon çerçevesinde ele alınmaktadır. Bu sistemlerin ise ağrı koşullarında karşılıklı olarak etkilenebildiği gösterilmiştir (22). Özellikle motor sistemin, ağrı ile ilişkili nöral süreçlerle etkileşim içinde olduğu ve bu etkileşimin ağrı modülasyonunda rol oynayabileceği bildirilmektedir (22) Ağrıya yönelik dikkat süreçlerinde ortaya çıkan değişimlerin, ağrı ile ilişkili uyaranların işlenişini etkileyebileceği belirtilmektedir. Bu etkilerin ise tutarlı olmadığı ifade edilmektedir. Ayrıca, bu etkilerin bağlama bağlı olarak değişkenlik gösterebildiği bildirilmektedir (23). **Duyusal, motor ve bilişsel süreçler arasındaki etkileşimlerin motor kontrol üzerinde dolaylı etkiler oluşturabileceği düşünülmektedir.**

Olumsuz beklentilerle ilişkili süreçler, korku-kaçınma modeli çerçevesinde ele alınmaktadır. Modelin bileşenlerinin kronik ağrı gelişimi ile ilişkili olduğu bildirilmektedir. (24). Ağrıya yönelik tehdit algısı ve buna eşlik eden psikososyal faktörlerin hareketten kaçınma ile ilişkili olduğu ifade edilmektedir. Ayrıca, bu durumun fonksiyonel kısıtlılık ile bağlantılı olduğu bildirilmektedir (25). Bu bulgular, söz konusu süreçlerin zaman içinde motor performans ve ağrı deneyimi ile ilişkili sonuçlar üzerinde rol oynayabileceğini düşündürmektedir. Dolayısıyla, beklentilerin yalnızca mevcut performansla sınırlı kalmayıp daha geniş klinik sonuçlarla ilişkili olabileceği değerlendirilmektedir. Buna karşılık ise olumlu beklentilerin motor performans üzerinde kolaylaştırıcı etkiler oluşturabildiği gösterilmektedir (26). Nitekim, bu beklentilerin hareket performansını artırabildiği, hareket süresini kısaltabildiği ve algılanan yorgunluk düzeyini azaltabildiği bildirilmektedir (26,27). Ayrıca, olumlu beklentiler ve dikkatle ilişkili süreçlerin motor performans ve öğrenme üzerinde kolaylaştırıcı etkiler oluşturabildiği ifade edilmektedir (28). Bu bulgular, söz konusu etkilerin yalnızca kısa vadeli performansla sınırlı olmayabileceğini göstermektedir. Aynı zamanda, bu etkilerin motor performans ile ilişkili daha geniş sonuçlara katkı sağlayabileceğini düşündürmektedir.

Rehabilitasyon süreci açısından değerlendirildiğinde ise bu mekanizmalar klinik sonuçlar üzerinde doğrudan belirleyici olmaktadır. Bireylerin tedaviye yönelik beklentileri, egzersize katılım ve tedaviye uyum ile ilişkili olup, bu durum rehabilitasyon sürecini etkileyebilmektedir (29). Korku-kaçınma inanç ve davranışları, kas iskelet sistemi ile ilişkili durumlarda iyileşmeyi sınırlayarak klinik sonuçları olumsuz etkileyebilmektedir (30). Bu nedenle, beklenti temelli süreçlerin sistematik olarak değerlendirilmesi ve uygun müdahalelerle yönlendirilmesi önem taşımaktadır. Bu yaklaşım, motor performansın geliştirilmesine ve daha etkili klinik sonuçların elde edilmesine katkı sağlayabilir.

SONUÇ

Bu çalışma, ağrı beklentisinin motor performans ve rehabilitasyon süreci üzerinde önemli bir belirleyici olduğunu ortaya koymaktadır. Olumsuz ağrı beklentilerinin tehdit algısını artırarak korku-kaçınma davranışlarını tetiklediği görülmektedir. Bunun, hareketten kaçınma, değişmiş motor stratejiler ve azalmış performans ile ilişkili olduğu bildirilmektedir. Buna karşılık ise olumlu beklentilerin ağrı algısını etkileyerek bireyin hareket sırasında güven duygusunu artırdığı ve motor performansı desteklediği anlaşılmaktadır.

Elde edilen bulgularla rehabilitasyon sürecinin yalnızca fiziksel iyileşmeye odaklanan bir yaklaşım olarak ele alınmasının yetersiz olduğunu göstermektedir. Bireyin ağrıya ilişkin inançları ve geçmiş deneyimlerinin de dikkate alınması gerektiğini göstermektedir. Korku-kaçınma davranışlarının azaltılması ve olumlu beklentilerin desteklenmesi ile tedaviye olan uyumu artırabilir ve motor performans ve fonksiyonel iyileşmeye katkı sağlayabilir. Tüm bu veriler ışığında, beklenti yönetiminin rehabilitasyonun ayrılmaz bir parçası olarak ele alınması gerekmektedir. Ayrıca, alandaki araştırmaların artırılmasının klinik uygulamalara önemli katkılar sağlayacağı öngörülmektedir.

Çıkar Çatışması

Yazar, çalışmanın hazırlanması ve yayımlanması sürecinde herhangi bir kişi ya da kurumla çıkar ilişkisi içinde olmadığını ifade etmektedir.

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RECURRENT HEPATIC AND PERITONEAL ECHINOCOCCOSIS: SURGICAL STRATEGY IN MULTIORGAN INVOLVEMENT

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Keywords: echinococcosis, recurrence, liver, peritoneal dissemination, enucleation, multiorgan involvement

Background: Cystic echinococcosis remains a significant public health problem in endemic regions. Despite advances in surgical techniques and antiparasitic therapy, recurrence rates remain considerable, particularly in cases with multiorgan involvement and peritoneal dissemination.

Objective: To evaluate the surgical strategy in recurrent and disseminated hepatic and peritoneal echinococcosis based on a clinical case and recent literature review.

Methods: A clinical case of a 21-year-old female patient with a history of two previous surgeries for hepatic and pulmonary echinococcosis who developed recurrent liver and disseminated peritoneal hydatid disease was analyzed. Clinical presentation, imaging findings, surgical management, and postoperative course were assessed.

Results: On February 13, 2026, open laparotomy was performed with enucleation of a hepatic hydatid cyst and removal of 10–12 peritoneal cysts. The operation lasted 5 hours. The postoperative period was uneventful, and the patient was discharged on the 4th postoperative day. Albendazole therapy and long-term radiological follow-up were recommended.

Conclusion: Recurrent and disseminated echinococcosis requires a radical yet parenchyma-preserving surgical approach combined with strict intraoperative protective measures and adequate postoperative antiparasitic therapy. Multidisciplinary management and long-term follow-up are essential to reduce recurrence risk.

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INTRODUCTION

Cystic echinococcosis is a zoonotic helminthic infection caused by Echinococcus granulosus. The disease is characterized by the formation of hydatid cysts in various organs, most commonly the liver and lungs. It remains endemic in many agricultural regions, including the South Caucasus.

Hepatic involvement accounts for approximately 60–70% of cases, while pulmonary localization represents 20–30%. In advanced or complicated cases, dissemination to the peritoneum, spleen, pelvic organs, and other intra-abdominal structures may occur.

According to the World Health Organization, echinococcosis continues to represent a significant global health burden, particularly in low- and middle-income countries.

Despite improvements in surgical and pharmacological treatment, recurrence rates range from 5% to 25%, especially in cases with multiple cysts or intraoperative spillage.

AIM OF THE STUDY to analyze the surgical strategy in recurrent and multiorgan disseminated echinococcosis based on a clinical case and contemporary literature data.

MATERIALS AND METHODS. This study is based on retrospective analysis of a clinical case and a review of international and local literature published between 2020 and 2025.

Diagnostic methods included:

- Abdominal ultrasonography (US)
- Computed tomography (CT)
- Serological testing (Echinococcus IgG)
- Liver function tests

Open surgical intervention was performed via midline laparotomy.

EPIDEMIOLOGICAL ASPECTS IN AZERBAIJAN

According to data from the Ministry of Health of the Republic of Azerbaijan, echinococcosis remains more prevalent in rural regions where livestock breeding is common.

Recent local studies (2020–2024) report:

- Recurrence rate in hepatic echinococcosis: 8–12%
- Recurrence in multiorgan involvement: 15–18%
- Need for reoperation in disseminated cases: up to 20%

A statistically significant correlation between multiorgan disease and recurrence risk has been reported ($p<0.05$).

CLINICAL CASE

A 21-year-old female patient was admitted with right upper quadrant abdominal pain and general weakness.

Medical history revealed:

1. First surgery: hepatic echinococcosis
2. Second surgery: hepatic and pulmonary echinococcosis

CT imaging demonstrated:

- An 12.9 cm cyst in the left hepatic lobe
- Multiple peritoneal cystic lesions measuring 10–12 cm
- Serology for Echinococcus IgG was positive. Liver function tests were within normal limits.

SURGICAL MANAGEMENT

On February, 2026, open midline laparotomy was performed.

Intraoperative findings included:

- Hydatid cyst in the left hepatic lobe 12-14cm
- Multiple peritoneal cysts (10–12 lesions)
- Cystic formations involving pelvic structures

Surgical steps:

- Thorough abdominal exploration
- Protective gauze packing to prevent spillage
- Enucleation of the hepatic cyst
- Removal of all visible peritoneal cysts
- Irrigation with scolicidal solution

Total operative time was 5 hours. Blood loss was minimal.

POSTOPERATIVE COURSE

The postoperative period was uneventful.

The patient received:

- Albendazole 10–15 mg/kg/day for 3 months
- Periodic monitoring of liver enzymes
- Ultrasonographic follow-up every 6 months

She was discharged on postoperative day 4 in stable condition.

DISCUSSION

Recurrence of echinococcosis is multifactorial and may result from:

- Intraoperative spillage of cyst fluid
- Incomplete pericystectomy
- Undetected microscopic daughter cysts
- Hematogenous spread
- Inadequate postoperative antiparasitic therapy

Meta-analyses published between 2020 and 2024 indicate:

- Recurrence after open surgery: 9–15%
- After laparoscopic surgery (selected cases): 5–10%
- After conservative treatment alone: up to 30%
- In disseminated cases, open surgery remains the preferred approach due to better exposure and control of contamination.
- Enucleation is considered a parenchyma-preserving technique that is especially beneficial in young patients.

In the present case, previous surgical interventions likely contributed to peritoneal contamination and subsequent dissemination.

LONG-TERM OUTCOMES AND PROGNOSIS

Risk reduction strategies include:

Radical surgical removal of all visible cysts

Adequate use of scolicidal agents

Prolonged albendazole therapy (3–6 months)

Long-term follow-up (2–5 years)

Early detection and appropriate management significantly improve prognosis.

CONCLUSION. Recurrent and disseminated hepatic echinococcosis represents a complex surgical condition requiring advanced expertise.

A radical yet liver-preserving surgical approach, combined with strict intraoperative precautions and adequate postoperative antiparasitic therapy, is essential for minimizing recurrence risk.

Multidisciplinary management and long-term monitoring remain crucial for optimal patient outcomes.

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DEVELOPMENT OF MEASUREMENT AND ASSESSMENT TOOLS FOR EVALUATİNG STUDENTS' CLİMATE LİTERACY İN THE SUBJECT OF BİOLOGY

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Abstract

Climate change poses significant environmental and social challenges worldwide and creates new responsibilities for education systems. In this context, developing and objectively assessing students' climate literacy has become increasingly important. This study aims to develop scientifically grounded assessment tools for measuring climate literacy in biology education. The object of the research is the development of climate literacy within the biology teaching process, while the subject focuses on its measurement mechanisms. The study was conducted during the 2024–2025 academic year among 8th and 9th-grade students. A mixed-method approach was applied, including achievement tests, Likert-scale questionnaires, and statistical analysis techniques. The dependent variable was climate literacy (knowledge, analytical skills, attitudes, and behavioral tendencies), and the independent variable was instructional characteristics. The findings revealed that students' overall climate literacy level was moderate, while analytical skills were comparatively less developed. The study recommends strengthening problem-based and inquiry-based learning approaches in biology education to enhance climate literacy outcomes.

Keywords: Climate literacy, biology education, assessment tools, environmental education, sustainable development

JEL Codes: I21, I29, Q54, Q56

INTRODUCTION

In the modern era, global climate change not only has significant impacts on ecological, social, and economic spheres, but also has created new challenges for the education system. Ensuring sustainable development and fostering citizens who possess environmentally responsible and scientifically grounded decision-making skills have become key priorities of school education. In this context, climate literacy emerges as a complex competence that encompasses not only students' acquisition of knowledge about climate change, but also their ability to analyze this knowledge, identify cause-and-effect relationships, assess risks, and demonstrate responsible behavior. The subject of Biology, covering concepts such as ecosystems, the biosphere, the carbon cycle, biodiversity, and human-nature interactions, provides a suitable scientific and methodological foundation for the development of climate literacy.

The relevance of the topic arises from the need not only to purposefully develop climate literacy within the teaching process, but also to objectively and reliably assess its level. Although ongoing educational reforms emphasize a competency-based approach, the systematic evaluation of climate literacy as a distinct measurement construct remains insufficiently developed in terms of scientific and

methodological support. Existing studies have mainly focused on the content of climate education and pedagogical approaches, while issues such as the development of measurement and assessment tools, the justification of their psychometric properties, and their alignment with the curriculum have been addressed to a limited extent. In this regard, the present study is aimed at addressing the existing scientific gap in the assessment of climate literacy (Arslan & Yıldırım, 2022).

The object of the study is the formation of students' climate literacy in the process of teaching Biology. The subject of the study is the development and implementation mechanisms of measurement and assessment tools that enable the determination of students' level of climate literacy within the framework of the Biology subject.

The main aim of the study is to develop scientifically grounded, reliable, and valid measurement instruments for assessing students' climate literacy in Biology. To achieve this aim, it is planned to identify the structural components of climate literacy, develop assessment criteria, design tests and alternative assessment tasks, and analyze the results of their implementation (Monreo et al., 2021).

The information base of the study consists of international scientific literature on climate change and climate education, competency-based curriculum documents, Biology subject programs, sources on assessment theory, and the results of the conducted empirical research.

During the research, methods such as theoretical analysis, comparative analysis, surveys and tests, expert evaluation, statistical processing, and psychometric analysis were used (Leiserowitz et al., 2022)

The limitations of the study are related to the selected age group and sample size, as well as the specific educational context in which the assessment tools were applied. In addition, the measurement of the behavioral and value components of climate literacy carries a certain degree of subjectivity.

The theoretical significance of the study is associated with the refinement of the structural model of climate literacy and the development of a methodological framework for its assessment. The practical significance lies in providing Biology teachers and educational researchers with practical assessment tools, enhancing the quality of the teaching process, and improving the effectiveness of climate-oriented education. These results are expected to contribute in the future to the improvement of the curriculum and the development of educational strategies aligned with sustainable development goals (Stevenson et al., 2022)

LITERATURE REVIEW

Climate change and climate education have been among the most widely studied areas in international scientific literature over recent decades. The conducted theoretical and empirical studies can be mainly grouped into three directions: (1) the conceptual foundations of climate literacy, (2) pedagogical approaches and content features of climate education, and (3) issues of assessing and measuring climate literacy.

In the first direction, climate literacy is presented as a multi-component construct. Researchers divide climate literacy into components such as knowledge (scientific foundations of the climate system), skills (data analysis and interpretation), attitudes and values

(environmental responsibility), and behavioral tendencies. These approaches demonstrate that climate literacy is not limited to the acquisition of factual information, but also encompasses critical thinking and decision-making skills. Although theoretical models form an important scientific basis for defining the structure of climate literacy, the operationalization of these models within specific subject contexts —particularly in Biology teaching—has not been sufficiently explored (Məmmədova, 2023).

In the second direction, the conducted studies emphasize the advantages of integrative and interdisciplinary approaches in teaching climate change. It has been shown that methods such as project-based learning, problem-based learning, inquiry-based activities, and the modeling of real-life situations increase students' interests in climate-related topics and deepen their understanding. Within the framework of Biology, connecting topics such as the carbon cycle, ecosystem stability, biodiversity, and anthropogenic impacts to the climate context is considered an effective pedagogical strategy. However, in most of these studies, the assessment of learning outcomes is limited to general test tasks, and no differentiated assessment is conducted across the structural components of climate literacy (Hüseynova, 2021).

The third direction–assessment issues–has been studied to a more limited extent. In existing empirical research, multiple-choice tests and survey questionnaires have primarily been used to determine the level of climate-related knowledge. In some studies, Likert-type scales have been applied to measure attitudes and behavioral tendencies. However, a number of these instruments have not been sufficiently developed in terms of psychometric justification, and their reliability and validity indicators have not been comprehensively reported. At the same time, the alignment of assessment tools with specific curriculum objectives and competency indicators remains an open issue.

Thus, the analysis of the literature shows that while the theoretical foundations of climate literacy have been sufficiently developed and significant results have been achieved in terms of instructional strategies, there are still scientific and practical gaps in the systematic, multi-component, and psychometrically grounded assessment of climate literacy within the context of Biology. In particular, the following issues remain insufficiently explored:

1. The integration of the structural model of climate literacy into the biology curriculum.
2. The development of comprehensive assessment tools covering knowledge, skills, and attitude components;
3. The statistical justification of the reliability and validity indicators of the developed instruments;
4. The mechanisms for using the results to improve the teaching process.

These gaps are directly related to the purpose of the present study. The article aims to identify a theoretically grounded structural model for assessing students' climate literacy in Biology, to develop measurement and assessment tools aligned with this model, and to analyze their applicability. Thus, the study seeks to contribute to improving the quality of climate-oriented education by addressing the scientific and practical gaps identified in the existing literature.

METHOD AND VARIABLES

A mixed-methodological approach was employed in the study to assess students' climate literacy. Although the research was primarily based on a quantitative measurement model, qualitative methods such as expert evaluation and content analysis were also used during the instrument development phase. At the initial stage, the structural components of climate literacy were identified, and measurable indicators for each component were defined. Subsequently, test items, scenario-based questions, and attitude scales were developed in accordance with these indicators. The developed assessment instruments were piloted on a sample group, and the obtained results were analyzed using statistical methods. Data processing included descriptive statistics, the calculation of internal consistency coefficients, and correlation analysis to determine relationships between variables.

Within the framework of the study, the main dependent variable was the level of students' climate literacy. Climate literacy was conceptualized as a multi-component construct and operationalized in terms of knowledge, skills, attitudes, and behavioral tendencies. The cognitive component was determined by the level of students' understanding of scientific concepts related to the climate system, causes and consequences of climate change, the carbon cycle, and anthropogenic impacts. The skill component was assessed based on indicators such as students' ability to analyze graphs and diagrams, establish cause-and-effect relationships, and make reasoned decisions in problem situations. The attitude and value component was measured through indicators such as environmental responsibility, sensitivity to climate issues, and attitudes toward sustainable development. Behavioral tendencies were identified based on students' self-assessment of their daily environmentally responsible habits (Wang & Jou, 2024).

As an independent variable, the characteristics of teaching climate-related topics in Biology and the applied pedagogical approaches were taken into account. Thus, the selected methodological framework made it possible to comprehensively analyze the structural components of climate literacy and to ensure the scientific validity of the developed measurement instruments.

PRELIMINARY RESULTS AND DISCUSSION

The developed assessment instruments were implemented in a pilot group consisting of 124 students from grades 8-9. Climate literacy was evaluated across four components: knowledge, analytical skills, attitudes, and behavioral tendencies. The overall results are as follows:

Table 1. Average Indicators by Climate Literacy Components

omponent	**aximumscore**	**eanscore(M)**	**Percentage(%)**	**tandarddeviation(SD)**
nowledge	0	8.6	62%	.2
nalyticalskills	5	3.2	53%	.8
ttitu	5	0.4	82%	.1

des				
behavioral tendencies	0	4.8	74%	7.9
verall indicators	00	7.0	67%	6.4

Source: Results of the study conducted by the author (2025).

The results show that students' overall level of climate literacy can be assessed as moderate (67%). The highest indicator was recorded for the attitude component (82%), while the lowest was for analytical skills (53%). The analysis of the knowledge component showed that 71% of students correctly identified the main causes of climate change; however, only 48% were able to provide a scientifically grounded explanation of the relationship between the carbon cycle and the climate system. In analytical tasks, 44% of the analysis of cause-and-effect relationships was 39%.

The high level of attitude indicators can be explained by the fact that 86% of students consider climate issues to be a serious global problem. However, in terms of real behavioral indicators (e.g., daily

energy saving or waste sorting), the level of consistent practical application was 61%, which indicates the existence of a certain gap between attitudes and actual behavior. The internal consistency of the assessment tool (Cronbach's alpha = 0.81) confirmed its high reliability. Correlation analysis between components showed a moderate positive relationship between knowledge and analytical skills (r = 0.62), while the relationship between knowledge and attitudes was weak (r = 0.28). This result confirms that climate literacy consists of multi-dimensional and relatively independent components.

The obtained results are consistent with the findings of international studies summarized in the literature review. Several studies have indicated that students' general level of climate-related knowledge is satisfactory, while analytical thinking and applied skills are relatively underdeveloped. At the same time, the fact that attitude indicators are higher than knowledge indicators is in line with previous empirical research.

However, the novelty of the present study lies in the application of a differentiated and psychometrically grounded measurement model across components. The results obtained show that, for the development of climate literacy in Biology, there is a particular need to strengthen analytical and applied skills. This, in turn, necessitates the broader use of problem-based and inquiry-oriented methods in the teaching process.

CONCLUSIONS AND RECOMMENDATIONS

The results of the conducted study indicate that the measurement and assessment tools developed for evaluating students' climate literacy in Biology are scientifically and methodologically sound and suitable for practical application. Climate literacy has been structured as a multi-component construct, and its operationalization in terms of knowledge, analytical skills, attitudes, and behavioral tendencies has been carried out. The results of pilot implementation revealed that students' overall level of climate literacy is at an average level; however, differences exist across components. In particular, it was found that analytical and applied skills are relatively underdeveloped, while attitude and value indicators are comparatively higher (Kaya & Yılmaz, 2021).

The psychometric properties of the assessment tool (internal consistency and intercomponent correlations) confirmed that it is a reliable measurement instrument. This demonstrates the feasibility of systematically and objectively assessing climate literacy. The results of the study also show that limiting climate literacy to factual knowledge alone is not an appropriate approach and that pedagogical strategies need to be revised to support its comprehensive development (Öztürk, 2023).

The theoretical significance of the study lies in refining the structural model of climate literacy and forming a methodological framework for its assessment. This model can serve as a conceptual basis for future research. At the same time, it contributes to the scientific literature by enabling the differentiated assessment of climate literacy across its components.

The practical significance is related to providing practical assessment tools for Biology teachers and curriculum developers. The developed instruments can be used for both formative and summative assessment within the teaching process and can help identify students'

strengths and weaknesses. This, in turn, enables the improvement of the quality of climate-oriented education and supports the development of educational strategies aligned with sustainable development goals.

The following directions are recommended for future research:

- Application of the measurement instruments across broader and more diverse age groups and determination of normative indicators;
- Investigation of the dynamics of climate literacy through longitudinal studies;
- Assessment of climate literacy in the context of other subjects based on an interdisciplinary approach;
- Measurement of the behavioral component based on objective observation and indicators of practical activities;
- Development of digital and interactive assessment platforms.

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APPLİCATİON AND PROSPECTS OF ARTİFİCİAL INTELLİGENCE İN PROJECT MANAGEMENT WİTHİN THE FRAMEWORK OF IPMA STANDARDS

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ABSTRACT

The integration of artificial intelligence (AI) into project management represents not only a technological shift but also a transformation of management philosophy. Within the IPMA framework, project management is viewed as a comprehensive system of competencies rather than a set of procedures. The ICB4 model divides these competencies into three domains—Perspective, People, and Practice—allowing AI to be understood as a "competence enhancer" that improves decision-making, visibility, and execution across all areas.

AI provides significant value, particularly in the early stages of projects, such as initiation and planning. It supports data-driven decision-making by enabling scenario modeling, forecasting risks, and refining project objectives. During execution and monitoring, AI enhances performance tracking, identifies risks early, and automates routine tasks. According to recent surveys, risk management and task automation are the most impactful areas of AI application, while generative AI tools like ChatGPT are widely used for communication, reporting, and documentation.

However, the IPMA framework emphasizes that human competencies remain essential. Skills such as leadership, communication, and ethical judgment cannot be replaced by AI. While AI reduces administrative burden and allows managers to focus more on people, it also introduces risks such as overreliance on technology and weakened accountability. Therefore, AI should complement—not replace—human decision-making.

At the organizational level, value from AI depends on governance, data quality, and process maturity. Standards such as OCB and PEB highlight that alignment among people, processes, and results is critical. Additionally, ethical considerations—such as transparency, accountability, data privacy, and human oversight—are central to the implementation of AI. Overall, AI offers substantial benefits across project management processes, but its success depends on proper integration with governance structures and human competencies. Future project managers will act as decision architects and ethical leaders, using AI as a strategic partner rather than a substitute for human expertise

Keywords: Artificial Intelligence in Project Management, IPMA Competence Framework, Risk Management and Automation, Ethical Governance and Human Oversight

Modern project management is no longer limited to controlling time, budget, and scope. Global competition, rapid technological change, multiple stakeholder groups, sustainability requirements, and

the sharp increase in data flows have transformed projects into more complex socio-technical systems. In such an environment, the integration of artificial intelligence into project management is not merely a technological innovation but also a reconstruction of management philosophy. The IPMA standards system provides a strong theoretical and practical foundation for understanding this transformation. IPMA ICB4 defines individual competencies, OCB defines organizational competence, and PEB describes project excellence; the 2025 IPMA AI Guidelines add a separate direction for the ethical and operational use of AI within this framework (IPMA, 2025).

The strength of the IPMA approach lies in the fact that it treats project management not as a set of procedures but as an ecosystem of competencies (IPMA, 2015). ICB4 divides this ecosystem into three main domains with 28 competence elements: "Perspective," "People," and "Practice". "Perspective" covers the project's connection with "Strategy", "Governance, Structures and Processes", "Compliance, Standards and Regulation", "Power and Interest", "Culture and Values"; "People" includes personal and social behaviors such as "Self reflection and self-management", "Personal integrity and reliability", "Personal Communication", "Relationships and Engagement", "Leadership", "Teamwork", "Conflict and Crysis", "Resourcefulness", "Negotiation", "Results orientation"; and "Practice" encompasses technical management elements such as "Project design", "Requirements and objectives", "Scope", "Time", "Organization and Information", "Quality", "Finance", "Resources", "Procurement", "Plan and Control", "Risk and opportunity", "Stakeholders" and "Change and transformation". This allows AI to be evaluated not as a tool replacing the project manager but as a "competence enhancer" that deepens decision-making, improves visibility, and increases execution speed across all three domains. At this point, artificial intelligence creates particular value in the early stages of project management (IPMA, 2015). During the initiation and planning phases, AI can process large volumes of data to support business case development, perform analogous estimations based on historical project data, refine critical success factors and KPIs, enable scenario modeling, and anticipate potential resource shortages. In relation to ICB4 competencies such as "Strategy," "Requirements and objectives," "Design," "Plan and control," and "Risk and opportunity," AI not only provides answers but also makes visible the assumptions on which the project is built. This enables decisions to be based on evidence and pattern recognition rather than intuition.

During the execution and monitoring phase, the role of AI becomes even more concrete. Algorithmic analysis can identify schedule deviations, performance trends, resource utilization, budget variances, and potential delays in the form of early warnings. According to the IPMA AI Survey 2024, the area where project management professionals see the highest potential for AI is risk management, ranking first with 79%; the second key area is task automation with 65% (IPMA, 2024). This is not coincidental: major problems in projects are often related to late risk detection and routine tasks distracting from strategic focus. AI can mitigate both issues through dynamic updates of risk registers, automatic identification of warning indicators, and rapid report generation. At the same time, the fastest-growing practical form of AI is not classical predictive analytics but generative AI. The IPMA

AI Survey 2024 shows that ChatGPT is currently the most popular tool among respondents using AI, with 90% adoption, followed by Copilot at 50% (IPMA, 2024). The same report highlights that project managers primarily interact with AI at the levels of communication, reporting, information synthesis, and decision support. In other words, the market has first rapidly adopted the function of an "intelligent PMO secretariat": meeting summaries, status updates, drafting risk texts, personalized stakeholder communication, and quick drafting of project documents are now among AI's everyday contributions. However, within the IPMA framework, the issue is not limited to technical productivity. The "People" domain of ICB4 shows that project success is impossible without personal and social competencies. Elements such as self-reflection, personal integrity, communication, relationship building, leadership, teamwork, conflict and crisis management, agility, negotiation, and result orientation shape the human side of the project manager. AI creates a dual effect in this area: on one hand, it frees the project manager from information overload and provides more time to work with people; on the other hand, it increases the risk of masking weak leadership, irresponsible decision-making, and communication breakdowns with technology. Therefore, according to IPMA logic, AI is not a substitute for a successful project leader; rather, it makes emotional intelligence, contextual judgment, and ethical responsibility even more critical. This transformation is also evident at the "Perspective" level. Thanks to AI, the project manager can build a more agile bridge between strategy and daily execution: it becomes possible to analyze market signals, stakeholder behavior, compliance requirements, and institutional risks in near real time. However, the "Power and interests" and "Culture and values" elements of ICB4 remind us that projects are not merely datasets. Informal power balances within organizations, political sensitivities, cross-cultural behavioral differences, and value systems are factors that AI models cannot calculate, but can determine the fate of a project. Thus, while AI strengthens strategic vision, interpreting context, ensuring decision legitimacy, and balancing interests remain the responsibility of the human manager.

One of the advantages of IPMA standards is that they systematically explain the transition from individual to organizational level. OCB defines organizational competence based on 18 elements and 5 groups, emphasizing the bridge between mission, vision, strategy, and actual results. This means that AI can create value in projects not only through individual initiatives but through institutional readiness. If data quality is poor, processes are not standardized, and roles and responsibilities are unclear, AI tools may increase local productivity but will not create value at the system level. The same logic is evident in PEB: project excellence arises from the alignment of "People & Purpose," "Processes & Resources," and "Project Results." From this perspective, AI generates real strategic value only when human factors, process architecture, and performance measurement support each other.

An important conclusion follows: the success of AI in project management depends less on the technology itself and more on how it is embedded in governance architecture. For example, an organization implementing AI for risk modules must also establish data entry standards, decision escalation mechanisms, accountability maps, and audit trails. Otherwise, the algorithm will generate warnings, but it will remain unclear who makes the decision, on what basis it is approved,

and at what threshold human intervention becomes mandatory. The IPMA AI Guidelines directly address this issue, presenting AI use as a distinct ethical-operational discipline. The key idea is that AI should not be added as a "module" to project processes but integrated with control mechanisms that preserve the legitimacy of management decisions.

The ethical and legal dimension is particularly sensitive. The IPMA AI Guidelines define principles such as transparency, accountability, privacy and data protection, fairness and bias reduction, security, and human oversight as the core foundation. The document clearly states that project managers must explain the purpose, limitations, and impacts of AI tools to stakeholders, document decision processes and data sources, establish compliance monitoring, and define response measures for unexpected outcomes. It also emphasizes that in high-risk and hard-to-explain decisions, AI should remain at an advisory level, with ultimate responsibility resting on humans. This approach shows that IPMA explains ethical project management not through technological neutrality but through a human-centered control principle (IPMA, 2025). The same document highlights the alignment of AI activities with organizational governance and their integration with AI management systems such as ISO/IEC 42001 ([ISO], 2023; IPMA, 2025). In practice, this means that AI tools used at the project level cannot exist outside the organization's overall AI policy. Procurement criteria, data storage rules, intellectual property risks, use of third-party platforms, audit, and compliance procedures must be predefined. Particularly for teams working with generative AI, prompt security, anonymization of confidential documents, validation of model outputs, and analysis of false positive/false negative impacts must be actively managed. Thus, AI is not only a "smart tool" but also a new type of governance object.

The current situation reflects a transition period. According to the IPMA AI Survey 2024, 42% of respondents reported not using AI at all in project management, 35% reported using it "a little," and 23% reported active use. The biggest barrier is lack of knowledge at 69%, followed by data privacy concerns at 60%; 29% cited unclear ROI, and 26% identified high costs as issues. In other words, the technology is accessible, but institutional trust, methodological knowledge, and economic justification are not yet fully developed. These indicators clearly explain why AI in project management remains largely at pilot, local, and experimental levels. Nevertheless, the outlook is generally optimistic. The same survey indicates that 70% of respondents are "likely" or "very likely" to adopt AI technologies within the next two years. The main driving force behind AI adoption is increased operational efficiency at 71%. This signals what the project office of the future will look like: a large portion of repetitive work will be automated, risk and performance monitoring will become more predictive, documentation will be faster, and simultaneously, the role of the project manager will evolve into that of a decision architect, ethical controller, change leader, and organizational translator. The strong project manager of the future will not be the one who operates tools but the one who transforms the opportunities created by tools into organizational value.

In conclusion, within the framework of IPMA standards, the application of artificial intelligence in project management reveals two parallel realities. First, AI can create measurable benefits across almost

all stages of project management—initiation, planning, execution, monitoring, communication, risk management, resource allocation, and change management. Second, these benefits are only achievable not through technology alone but in combination with the principles of competence, governance, ethical responsibility, and organizational readiness emphasized by IPMA. Therefore, in the near future, successful organizations will be those that see AI not as an alternative to the project manager but as an intellectual partner that enhances strategic thinking, ethical judgment, and value creation capabilities. IPMA logic confirms this: no matter how powerful technology becomes, ultimate responsibility for project success remains with human competence, organizational maturity, and the legitimacy of decisions.

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PAMUKTA DÜŞÜK SICAKLIK STRESİ VE FİZYOLOJİK ETKİLERİ

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ÖZET

Küresel tekstil endüstrisinin temel doğal elyaf kaynağı olan pamuk (*Gossypium spp.*), lif üretiminin yanı sıra tohumundaki yağı ile insan beslenmesine, yüksek proteinli küspesiyle de hayvancılık sektörüne ham madde sağlayan çok yönlü bir endüstri bitkisidir. Ayrıca çırçırlama sonrası elde edilen linter, kimya ve kozmetik gibi pek çok sanayi kolunda stratejik bir bileşen olarak kullanılmaktadır. Ancak, değişen iklim koşullarıyla birlikte pamuk yetiştiriciliği, bitkinin çimlenme aşamasından hasat dönemine kadar olan tüm yaşam döngüsünü tehdit eden abiyotik stres faktörleriyle karşı karşıyadır. Özellikle düşük sıcaklık stresi; pamuğun morfolojik gelişimini, fizyolojik süreçlerini, fotosentez kapasitesini, verimini ve lif kalitesini doğrudan kısıtlayan en kritik faktörlerden biri haline gelmiştir. Bu durum, sürdürülebilir üretim için iklim değişikliğine toleranslı genotiplerin geliştirilmesini zorunlu kılmaktadır. Pamuk üretiminde düşük sıcaklığın olumsuz etkilerini minimize etmek amacıyla; düşük sıcaklık koşullarına uygun pamuk çeşitlerinin geliştirilmesinin yanı sıra uygun malçlama teknikleri ve ekim zamanı gibi agronomik uygulamaların, spesifik bitki besleme programlarının ve biyoteknolojik müdahalelerin bir arada yürütüldüğü entegre bir yönetim stratejisinin benimsenmesi, sektörün geleceği açısından hayati önem taşımaktadır.

Anahtar Kelimler: Pamuk, abiyotik stres, düşük sıcaklık, fizyoloji, verim

LOW TEMPERATURE STRESS AND ITS PHYSIOLOGICAL EFFECTS IN COTTON

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ABSTRACT

Cotton (*Gossypium* spp.), the primary natural fiber source for the global textile industry, is a versatile industrial plant that provides raw materials for human nutrition through its seed oil and for the livestock sector through its high-protein meal, in addition to fiber production. Furthermore, the linter obtained after ginning is used as a strategic component in many industries, including chemicals and cosmetics. However, with changing climate conditions, cotton cultivation faces abiotic stress factors that threaten the entire life cycle of the plant, from germination to harvest. Low temperature stress, in particular, has become one of the most critical factors directly limiting cotton's morphological development, physiological processes, photosynthetic capacity, yield, and fiber quality. This situation necessitates the development of climate change-tolerant genotypes for sustainable production. To minimize the negative effects of low temperatures in cotton production, adopting an integrated management strategy that combines the development of cotton varieties suitable for low temperatures with agronomic practices such as appropriate mulching techniques and planting time, specific plant nutrition programs, and biotechnological interventions is vital for the future of the sector.

Keywords: Cotton, abiotic stress, low temperature, physiology, yield

GİRİŞ

Pamuk (*Gossypium hirsutum* L.), dünya genelinde yaygın olarak yetiştirilen lif bitkisi olup küresel tekstil endüstrisinin hammadde ihtiyacının oldukça önemli bir bölümünü karşılamaktadır. Ekonomik değeri yalnızca lif üretimiyle sınırlı kalmayıp, çiğit yağı, hayvan yemi ve biyoyakıt gibi yan ürünleriyle de tarımsal ekonomide stratejik bir konuma sahiptir (Zafar vd., 2018).

Sıcaklık, pamuğun çimlenmesinden hasadına kadar her aşamayı doğrudan etkileyen temel çevresel faktördür. Tropik ve subtropik kökenli türler, düşük sıcaklık koşullarına karşı genellikle sınırlı bir savunma kapasitesine sahiptir. Pamuk bitkisi de bu türlerden biri olup, vejetatif ve generatif gelişim için 25-35 °C aralığındaki sıcaklıklara ihtiyaç duymaktadır (Zafar vd., 2018). Toprak sıcaklığı 18 °C'nin altına düştüğünde tohumun çimlenmesi belirgin biçimde yavaşlamakta; 10 °C civarında ise metabolik süreçler neredeyse tamamen durmaktadır (Edmisten ve Collins, 2024). Sıcaklık eşiklerinin altına inilmesi durumunda, bitkide çeşitli stres tepkilerine yol açarak geri dönüşümü güç olan bazı yapısal ve işlevsel bozulmalara neden olabilmektedir.

Düşük sıcaklık stresi, bitki biyolojisinde iki kategoride ele alınmaktadır. Soğuklama stresi (chilling, 0-15 °C), hücre içi donma gerçekleşmeksizin enzim aktivitesinin azalması, hücre membran akışkanlığında meydana gelen değişiklikler ve metabolik süreçlerin yavaşlamasıyla ilişkilidir. Donma stresi (freezing, <0 °C) ise apoplastik ve hatta sitoplazmik buz kristallerinin oluşumu sonucu hücre duvarı ve zarının mekanik tahribatına yol açar (Yadav, 2010; Ruelland vd., 2009). Pamuk her iki stres türüne karşı yüksek duyarlılık göstermekte olup, özellikle çimlenme ve fide aşamalarında soğuklama hasarından ciddi şekilde etkilenmektedir. (Bölek vd., 2013). İklim değişikliğine bağlı olarak ortalama küresel sıcaklıklar da artış gözlense de ani soğuk hava dalgaları gibi ekstrem iklim olaylarının sıklığı ve şiddeti de paralel şekilde yükselmektedir. (Meehl vd., 2007). Kuzey Çin, Orta Asya, ABD Güney Kuşağı ve Türkiye'nin Güneydoğu Anadolu Bölgesi gibi pamuk yetiştirme alanlarında bahar döneminde yaşanan beklenmedik soğuklar, fide kayıplarına ve önemli ekonomik zararlara yol açabilmektedir. Bu durum, pamuğun soğuk stresine ilişkin fizyolojik süreçlerin ve dayanıklılık mekanizmalarının anlaşılmasını zorunlu kılmaktadır.

Düşük sıcaklık stresinin pamuk üzerindeki etkileri çok boyutludur. Morfolojik düzeyde kök ve sürgün gelişiminin engellenmesi, yaprak alanının azalması ve bitki boyunun kısalması gözlemlenmektedir. Fizyolojik düzeyde ise hücre zarı bütünlüğünün bozulması, fotosentez hızının düşmesi, enzim aktivitelerinin değişmesi, oksidatif stresin artması ve ozmotik dengesizlik gibi ciddi sonuçlar ortaya çıkmaktadır (Li vd., 2024; Dhaliwal vd., 2024). Tüm bu fizyolojik bozulmalar bir araya geldiğinde verim düşer ve lif kalitesi azalır.

Bu derlemede, düşük sıcaklık stresinin pamukta tetiklediği fizyolojik değişimler güncel araştırma bulguları ışığında ele alınmaktadır. Bu doğrultuda hücre zarı hasarı, fotosentetik performans, oksidatif stres ve antioksidan savunma mekanizmaları, ozmotik düzenleme, hormonal yanıtlar, su ilişkileri ve verim üzerine etkileri gibi temel başlıklar sırasıyla incelenecektir.

1. DÜŞÜK SICAKLIK STRESİNİN HÜCRE ZARI ÜZERİNDEKİ ETKİLERİ

Hücre zarı, düşük sıcaklık stresine karşı en hassas hücresel yapılardan biridir. Bitki hücre zarları fosfolipid çift tabakasından oluşmakta olup bu tabakanın fiziksel durumu sıcaklığa bağlı olarak değişmektedir. Normal koşullarda sıvı-kristal fazda bulunan membran lipidleri, düşük sıcaklıklarda jel fazına geçiş yapar ve bu durum membranın akışkanlığını önemli ölçüde azaltır

(Bhattacharya, 2022). Sıcaklıklar optimumun altına düştükçe, reaksiyon hızları büyük ölçüde geri dönüşümlü bir şekilde azalır; ancak belirli bir sıcaklığın altında, oksidatif stres ve membran yapısındaki değişiklikler, optimum metabolizmanın yeniden başlaması için onarım gerektiren geri dönüşümsüz hasara neden olabilir. Bu durum, düşük sıcaklık stresinin bitkide yalnızca geçici bir yavaşlamaya değil, kalıcı yapısal bozulmalara da yol açabileceğini ortaya koymaktadır. Pamuk fidelerinde soğuk stres uygulamalarının ardından elektrolit sızıntısında belirgin artışlar kaydedilmiştir; bu durum membran bütünlüğünün bozulduğunun doğrudan bir kanıtıdır (Dhaliwal vd., 2021). Membran hasarının şiddeti, malondialdehit (MDA) birikimi ile ölçülmektedir. MDA, doymamış yağ asitlerinin lipid peroksidasyonu sonucunda oluşan bir aldehit olup, oksidatif membran hasarının en yaygın kullanılan biyokimyasal göstergesidir. Soğuk stresine maruz kalan pamuk bitkilerinde MDA düzeylerinin kontrole kıyasla anlamlı düzeyde arttığı çok sayıda çalışmayla kanıtlanmıştır (Cheng vd., 2023; Han vd., 2025).

Hücre dışına sızan potasyum, kalsiyum ve diğer iyonlar, hücre içi iyon homeostazını alt üst ederek enzim aktivitelerini sekteye uğratmaktadır. Ayrıca, lipid peroksidasyonunun nihai ürünü olan malondialdehit (MDA) düzeyi, soğuk stres şiddetiyle doğru orantılı biçimde artmaktadır. Chen vd. (2023) ve Lu vd. (2020), farklı pamuk genotiplerinde MDA birikiminin soğuğa duyarlılıkla pozitif korelasyon gösterdiğini ortaya koymuştur. Membran lipid bileşimi, bitkinin soğuğa toleransını belirleyen kritik faktörlerden biridir. Soğuğa dayanıklı pamuk genotiplerinde membran lipidlerindeki doymamış yağ asidi oranının daha yüksek olduğu ve bu durumun düşük sıcaklıklarda membran akışkanlığını koruduğu belirlenmiştir (Dhaliwal vd., 2024). Yağ asidi desatüraz enzimleri, doymuş yağ asitlerini doymamışlara dönüştürerek membran akışkanlığını artırmakta ve böylece düşük sıcaklık toleransına katkıda bulunmaktadır. Soğuğa dayanıklı çeşitlerde bu enzimlerin ekspresyonunun stres koşullarında artış gösterdiği rapor edilmiştir. Bununla birlikte, hücre zarı hasarı yalnızca lipid peroksidasyonuyla sınırlı kalmamaktadır. Düşük sıcaklıklar, membran proteinlerinin ve glikoproteinlerinin yapısını da etkileyerek, hücre zarının sinyal iletim işlevlerini bozabilmektedir. Özellikle kalsiyum (Ca^{2+}) kanalları ve kalsiyum bağımlı protein kinazlar, soğuk stres sinyalinin algılanması ve iletilmesinde kritik rol oynamaktadır. Düşük sıcaklık, hücre zarındaki kalsiyum kanallarını aktive ederek sitoplazmik Ca^{2+} konsantrasyonunun artmasına yol açar ve bu artış soğuk stres sinyal kaskadının başlatılmasını sağlar (Luo vd., 2024).

2. DÜŞÜK SICAKLIK STRESİNİN FOTOSENTETİK PERFORMANS ÜZERİNDEKİ ETKİLERİ

Sıcaklık düştüğünde bitkide ilk sekteye uğrayan süreçlerin başında fotosentez gelir. Soğuk stres koşullarında fotosentetik kapasite geriler; karbon asimilasyonu ve enerji üretimi bundan doğrudan etkilenir. (Li vd., 2024). Pamuk yapraklarında düşük sıcaklık stresinin fotosentez üzerindeki etkileri, gaz değişim parametreleri ve klorofil floresans ölçümleriyle takip edilir.

2.1. Karbon Asimilasyonu ve Gaz Alışverişindeki Değişimler

Li vd. (2024), soğuğa toleranslı pamuk çeşidi ZM36 üzerinde yaptıkları çalışmada, farklı sıcaklık seviyelerinin (25 °C kontrol, 15 °C, 10 °C ve 4 °C) fotosentetik parametreler üzerindeki etkilerini incelemiştir. Elde edilen sonuçlar, sıcaklık düştükçe net fotosentez hızının (Pn), stoma iletkenliğinin (Gs) ve terleme hızının (Tr) önemli ölçüde azaldığını göstermiştir. Özellikle 4 °C'de bu parametrelerdeki düşüş en belirgin düzeye ulaşmıştır. Buna karşın, hücreler arası CO_2 konsantrasyonunun (Ci) arttığı gözlemlenmiştir; bu durum, fotosentez kaybının salt stomal kısıtlamayla açıklanamayacağını, Calvin döngüsü enzimlerinin de inhibe olduğunu düşündürmektedir.

Stoma iletkenliğindeki azalma, bitkinin su kaybını sınırlamaya yönelik bir savunma mekanizması olarak değerlendirilmekle birlikte, CO_2 alımının da kısıtlanmasına yol açarak fotosentez hızını düşürmektedir. Düşük sıcaklıklarda Rubisco enziminin aktivasyonunun yavaşlaması ve Rubisco aktivaz enziminin düşük sıcaklık hassasiyeti, karboksilasyon kapasitesini doğrudan etkilemektedir (Snider vd., 2022). Soğuk stresinin tetiklediği stoma kapanması yaprak sıcaklığında ek düşüşlere neden olmakta ve böylece stres koşullarının şiddetlenmesine yol açabilmektedir.

2.2. Klorofil Floresans ve PSII Performansı

Klorofil floresans ölçümleri, fotosentetik aparatın işlevselliğini değerlendirmek için kullanılan hızlı ve yıkımsız bir yöntemdir (Snider vd., 2018). Düşük sıcaklık stresinde PSII'nin maksimum fotokimyasal verimliliğini gösteren Fv/Fm oranının önemli ölçüde düştüğü ve Fo/Fm oranının arttığı bildirilmiştir (Li vd., 2024). Fv/Fm oranındaki bu düşüş, PSII reaksiyon merkezlerinin fotoinhibisyona uğradığını ve tilakoit membranlarındaki elektron taşıma zincirinin hasar gördüğünü göstermektedir.

Performans indeksi (PIabs), fotosentetik performansın bütünsel bir göstergesi olarak Fv/Fm'den daha hassas bir parametre olarak kabul edilmektedir. Soğuk stresine maruz kalan pamuk yapraklarında PIabs değerinin dramatik şekilde azaldığı rapor edilmiştir (Zhu vd., 2024). Bu durum, düşük sıcaklığın yalnızca PSII reaksiyon merkezlerini değil, aynı zamanda anten pigmentlerinin ışık toplama kapasitesini ve elektron taşıma zincirinin her aşamasını olumsuz etkilediğini ortaya koymaktadır.

3. OKSİDATİF STRES VE ANTİOKSİDAN SAVUNMA MEKANİZMALARI

Düşük sıcaklık stresi, bitki hücrelerinde reaktif oksijen türlerinin (ROS) aşırı birikmesine neden olmaktadır. Süperoksit radikali (O_2^-), hidrojen peroksit (H_2O_2) ve hidroksil radikali ($OH\cdot$) gibi ROS türleri, normal metabolik süreçlerin yan ürünleri olarak düşük seviyelerde üretilmekte ve hücresel sinyal molekülleri olarak görev almaktadır. Ancak, soğuk stresi koşullarında elektron taşıma zincirinin bozulması, ROS üretimin kontrolsüz şekilde artmasına ve sonuçta oksidatif hasarın ortaya çıkmasına yol açmaktadır.. (Fan vd., 2014).

3.1. ROS Üretimi ve Oksidatif Hasar

Soğuk stresinde ROS üretiminin temel kaynakları kloroplastlar, mitokondri ve peroksizomlar oluşturmaktadır. Kloroplastlarda fotosentetik elektron taşıma zincirinin bozulması, fazla enerjinin moleküler oksijene aktarılmasına ve buna bağlı olarak süperoksit radikallerinin oluşumuna neden olmaktadır. Mitokondride ise solunum zincirinde meydana gelen elektron kaçağı ROS üretimini yükseltir. Aşırı miktarda biriken ROS; lipid peroksidasyonu, protein oksidasyonu ve DNA hasarı gibi oksidatif süreçleri tetikleyerek hücresel işlevlerde ciddi şekilde bozulmalara yol açar. (Cheng vd., 2023).

Pamuk fidelerinde soğuk stres uygulamasının ardından H_2O_2 ve O_2^- birikiminin belirgin şekilde arttığı ve buna paralel olarak MDA düzeylerinin yükseldiği gösterilmiştir (Han vd., 2025). Bu oksidatif hasarın izleri, öncelikle membran lipidlerinde ve fotosentetik pigmentlerde ortaya çıkar; enzim aktivitelerinin gerilemesi de sürecin bir parçasıdır. Yapılan karşılaştırmalar, soğuğa duyarlı pamuk genotiplerde hasarın çok daha ağır seyrettiğini, toleranslı genotiplerin ise antioksidan savunma mekanizmaları sayesinde bu yıkımı sınırladığını ortaya koymuştur.

Pamuğun düşük sıcaklık stresine verdiği yanıtın, birden fazla metabolik yolu düzenleyen karmaşık bir gen ağı tarafından yönetildiğini göstermektedir (Li vd.,2024)

3.2. Enzimatik Antioksidan Savunma Sistemi

Bitkiler, ROS birikiminin hücreye verdiği zararı sınırlamak üzere bitkiler çok bileşenli bir enzimatik savunma sistemine sahiptir. Bu sistemin temel bileşenleri süperoksit dismutaz (SOD), katalaz (CAT), peroksidaz (POD), askorbat peroksidaz (APX) ve glutatyon redüktaz (GR) enzimleridir (Han vd., 2025). SOD, süperoksit radikallerini H_2O_2'ye dönüştürerek ilk savunma hattını oluşturur; CAT ve APX ise H_2O_2'yi suya indirger. Soğuğa toleranslı pamuk genotiplerinde, düşük sıcaklık stresine yanıt olarak SOD, CAT ve POD enzim aktivitelerinin önemli ölçüde arttığı rapor edilmiştir (Zhu vd., 2024). Zhu vd. (2024), ekzojen melatonin uygulamasının pamukta antioksidan enzim aktivitelerini artırarak soğuk toleransını iyileştirdiğini bildirmiştir. Buna karşın, soğuğa duyarlı genotiplerde enzim aktivitelerindeki artışın yetersiz kaldığı ve ROS birikiminin kontrol edilemediği gözlemlenmiştir.

3.3. Enzimatik Olmayan Antioksidan Savunma Sistemi

Enzimatik antioksidanların yanı sıra, bitkiler askorbik asit (C vitamini), glutatyon (GSH), karotenoidler, tokoferoller (E vitamini) ve fenolik bileşikler gibi enzimatik olmayan antioksidanlarla da ROS'a karşı mücadele etmektedir. Askorbat-glutatyon döngüsü (Halliwell-Asada döngüsü), H_2O_2'nin detoksifikasyonunda özellikle etkilidir. Bu döngüde APX, H_2O_2'yi askorbat kullanarak indirgerken, oluşan dehidroaskorbat ve okside glutatyon, sırasıyla dehidroaskorbat redüktaz (DHAR) ve glutatyon redüktaz (GR) tarafından yeniden indirgenmektedir.

Soğuğa toleranslı pamuk çeşitlerinde askorbik asit ve glutatyon düzeylerinin stres koşullarında daha yüksek seviyelerde korunduğu ve askorbat-glutatyon döngüsünün daha etkin çalıştığı bildirilmiştir (Han vd., 2025). Fenilpropanoid yolağı üzerinden sentezlenen flavonoidler ve fenolik asitler de güçlü antioksidan kapasiteye sahip olup, soğuk stresinde birikimlerinin arttığı rapor edilmiştir.

4. OZMOTİK DÜZENLEME VE OZMOTIK KORUYUCU MADDELERİN BİRİKİMİ

Düşük sıcaklık stresi, bitki hücrelerinde ozmotik dengeyi bozarak hücresel dehidrasyona yol açabilmektedir. Bitkiler bu strese karşı çeşitli ozmotik düzenleyici maddelerin (osmoprotektanlar) birikimini artırarak hücre turgor basıncını korumaya çalışmaktadır. Prolin, çözünür şekerler, çözünür proteinler ve glisin betain bu osmoprotektanların başlıcalarıdır (Theocharis vd., 2012).

4.1. Prolin Birikimi

Prolin, bitkilerde stres koşullarında en fazla biriken amino asitlerden biri olup düşük sıcaklık stresinde kritik bir koruyucu rol üstlenmektedir. Prolin, ozmotik düzenlemenin yanı sıra serbest radikallerin temizlenmesinde, hücresel redoks dengesinin korunmasında ve protein ile membran yapılarının stabilize edilmesinde de görev almaktadır. Soğuk stresine maruz kalan

pamuk fidelerinde prolin birikiminin kontrole kıyasla anlamlı düzeyde arttığı çok sayıda çalışmayla gösterilmiştir (Dhaliwal vd., 2024; Cheng vd., 2023).

Prolin biyosentezi, Δ^1-pirolin-5-karboksilat sentetaz (P5CS) enzimi tarafından katalize edilmektedir. Soğuk stresinde *GhP5CS* geninin ekspresyonunun arttığı ve buna bağlı olarak prolin birikiminin yükseldiği gösterilmiştir. Soğuğa toleranslı çeşitlerde prolin birikiminin daha hızlı ve daha yüksek seviyelere ulaştığı, duyarlı çeşitlerde ise bu yanıtın yetersiz kaldığı belirlenmiştir. Cheng vd. (2023), *SikCOR413PM1* geninin aşırı ekspresyonunun pamuk fidelerinde prolin düzeylerini %40-55 oranında artırdığını ve bu artışın soğuk toleransıyla pozitif korelasyon gösterdiğini rapor etmiştir.

4.2. Çözünür Şeker Birikimi

Çözünür şekerler (sakkaroz, glukoz, fruktoz, raffinoz ve trehaloz), düşük sıcaklık stresinde hem ozmotik düzenleyici hem de kriyoprotektan olarak işlev görmektedir. Bu şekerler, hücre zarı ve proteinlerin etrafında koruyucu bir tabaka oluşturarak yapısal bütünlüğün korunmasına katkıda bulunmaktadır. Özellikle raffinoz ailesine ait oligosakkaritler (RFO'lar), soğuk stresinde cam durumu (vitrifikasyon) oluşturarak hücre içi buz kristalleşmesini önlemede önemli bir rol üstlenmektedir (Theocharis vd., 2012).

Pamuk bitkilerinde soğuk stres uygulamasının ardından çözünür şeker içeriklerinin belirgin şekilde arttığı rapor edilmiştir. Cheng vd. (2023), transgenik pamuk bitkilerinde 4 °C stres altında çözünür şeker düzeylerinin yabani tipe kıyasla %32-43 oranında daha yüksek olduğunu göstermiştir. Nişasta yıkım enzimleri olan amilaz ve nişasta fosforilaz, soğuk stresinde aktive olarak nişastanın çözünür şekerlere dönüşümünü hızlandırmakta ve böylece ozmotik düzenlemeye katkıda bulunmaktadır.

4.3. Çözünür Protein Birikimi

Çözünür proteinler de soğuk stresinde ozmotik düzenlemeye katılmaktadır. Soğuğa yanıt olarak sentezlenen dehidrinler, LEA (Late Embryogenesis Abundant) proteinleri ve ısı şoku proteinleri gibi stres proteinleri, hücresel yapıların korunmasında katkı sağlamaktadır. Özellikle Dehidrinler, yüksek hidrofilik yapıları sayesinde protein ve membran yüzeylerinde koruyucu bir tabaka oluşturarak su kaybını sınırlandırmaktadır. COR (Cold-Responsive) proteinleri de soğuk stresinde gen ekspresyonunun artmasıyla biriken ve hücresel koruma sağlayan protein grubudur. (Hwarari vd., 2022).

5. HORMONAL YANITLAR VE SİNYAL İLETİMİ

Bitki hormonları, düşük sıcaklık stresine verilen yanıtların düzenlenmesinde oldukça önemlidir. Absisik asit (ABA), jasmonik asit (JA), etilen, oksin, giberellinler ve brassinosteroidler, soğuk stres yanıtlarını düzenleyen başlıca fitohormonlardır (Dev vd., 2024).

5.1. Absisik Asit (ABA)

ABA, düşük sıcaklık stresine verilen yanıtlarda önemli rol oynayan bir bitki hormondur. Soğuk stres algılandığında, ABA biyosentez yolağındaki genlerin ekspresyonu hızla artmakta ve endojen ABA düzeyleri yükselmektedir. ABA, stomatal kapanmayı tetikleyerek su kaybını azaltır, ozmotik düzenleyici maddelerin birikimini teşvik eder ve soğuğa yanıt veren (COR) genlerin ekspresyonunu uyarmaktadır (Manasa vd., 2021; Liu vd., 2022). ABA sinyal yolağındaki anahtar bileşenler olan PYR/PYL reseptörleri, PP2C fosfatazlar ve SnRK2 kinazlar, soğuk stres sinyalinin çekirdeğe iletilmesinde görev yapmaktadır. Pamukta yapılan çalışmalarda, ekzojen ABA uygulamasının soğuk toleransını artırdığı ve ABA biyosentez genlerinin ekspresyonunun soğuk stresinde hızla yükseldiği gösterilmiştir (Luo vd., 2024).

5.2. Jasmonik Asit (JA) ve Etilen

Jasmonik asit, soğuk stres yanıtlarında ABA ile sinerjik olarak çalışmaktadır. JA biyosentezinin soğuk stresinde arttığı ve bu artışın soğuğa tolerans genlerinin ekspresyonunu uyardığı bildirilmiştir. JA, ICE-CBF-COR sinyal yolağı ile etkileşime girerek soğuk aklimatizasyon sürecini desteklemektedir. Etilen ise soğuk stres yanıtlarında hem pozitif hem de negatif düzenleyici olarak görev yapabilmektedir. Düşük konsantrasyonlarda etilen, stres toleransını artırıcı etki gösterirken, yüksek konsantrasyonlarda senescence (yaprak yaşlanması) ve yaprak dökümünü hızlandırabilmektedir.

5.3. Oksin ve Gibberellinler

Düşük sıcaklık stresi, oksin ve gibberellin metabolizmasını da etkilemektedir. Soğuk stresinde oksin taşınımının yavaşladığı ve buna bağlı olarak kök ve sürgün gelişiminin engellendiği gösterilmiştir. Gibberellin düzeylerinin düşük sıcaklıklarda azalması, DELLA proteinlerinin birikmesine ve büyümenin baskılanmasına yol açmaktadır. Bu hormonal değişimler, bitkinin büyüme hızını yavaşlatarak enerji kaynaklarını stres savunmasına yönlendiren adaptif bir strateji olarak değerlendirilmektedir. Pamuk tohumlarının çimlenmesinde, soğuğa toleranslı çeşitlerde IAA, sitokinin ve GA_3 düzeylerinin daha yüksek, ABA düzeylerinin ise daha düşük olduğu belirlenmiştir (Zheng vd., 2020).

6. TOHUM ÇİMLENMESİ, SU EMİLİMİ VE KÖK GELİŞİMİ ÜZERİNDEKİ ETKİLERİ

Pamuk tohumunun çimlenmesi için optimum sıcaklık 30 °C, minimum sıcaklık ise 12 °C'nin üzerindedir (Borth, 1997). Pamuk tohumu çimlenme esnasında düşük sıcaklıklara karşı toleransı düşüktür. Christiansen (1968), pamuk tohumlarının 30 dakika boyunca düşük sıcaklıklara maruz bırakıldıktan sonra çimlenmenin azaldığını ve kök anormalliklerinin oluştuğunu gözlemlemiştir. Ayrıca, su absorbsiyonu sırasında 12 saatlik daha uzun süreli soğuklamanın tohumlarda kalıcı hasara ve dolayısıyla kökçüğün ortaya çıkamamasına neden olduğunu belirtmiştir.Tohum su emilimi (imbibisyon), tohum çimlenmesinin ilk aşaması olup bunu kısa süre sonra solunumda artışlar takip eder (Rajjou vd., 2012). Tohum su emilim hızının, özellikle tohum kabuğu geçirgenliği, tohum nem içeriği, suyun sıcaklığı ve tohum tarafından

suyun emilme hızı gibi tohum ve suyun özelliklerine büyük ölçüde bağlı olduğu düşünülmektedir (Vertucci, 1989).

Çimlenme ve fide gelişimi, pamuğun düşük sıcaklık stresine en hassas olduğu dönemlerdir. Erken ilkbahar ekimlerinde yaşanan soğuk hava koşulları, tohum çimlenmesini ciddi şekilde geciktirebilir veya tamamen engelleyebilir. Pamuk tohumları 15 °C'nin altındaki sıcaklıklarda çimlenme güçlüğü yaşamakta, 10 °C'nin altında ise çimlenme hemen hemen durmaktadır (Zakaria, 2017). Soğuk sıcaklıklarda çimlenmenin yavaşlaması, toprak patojenlerine maruz kalma süresini uzatarak fide kayıplarının artmasına da neden olabilmektedir.

Düşük sıcaklık stresinin pamuk tohumlarının çimlenmesi üzerindeki olumsuz etkileri, çimlenme potansiyeli, çimlenme oranı, çimlenme indeksi ve çimlenme hızı gibi parametrelerde kendini göstermektedir (Han vd., 2025). Soğuğa toleranslı çeşitlerde bu parametrelerin daha az etkilendiği ve çimlenme gücünün daha iyi korunduğu bildirilmiştir. Dhaliwal vd. (2024), yağ asidi doymamışlık derecesi yüksek olan pamuk çeşitlerinin düşük sıcaklıkta daha iyi çimlenme performansı gösterdiğini rapor etmiştir.

Soğuk stresi, fizyolojik aktiviteyi, biyokimyasal metabolizmayı, büyümeyi, gelişmeyi ve nihayetinde ürün verimini önemli ölçüde etkileyebilmektedir. Fide aşamasında düşük sıcaklık stresi, hipokotil uzamasının yavaşlamasına, yaprak alanının küçülmesine, bitki boyunun kısalmasına ve toplam biyokütlenin azalmasına neden olmaktadır. Özellikle kotiledon yapraklarında klorozis ve nekrotik lekeler gözlemlenebilmektedir. Ciddi soğuk stres koşullarında solgunluk, yaprak kuruması ve fide ölümleri meydana gelebilmektedir. Fide kayıpları %15'in üzerinde olduğunda, pamuğun büyüme mevsimi gecikebilmekte ve verim ile lif kalitesi olumsuz etkilenebilmektedir (Fahad vd., 2014).

7. VERİM VE LİF KALİTESİ ÜZERİNDEKİ ETKİLER

Düşük sıcaklık stresinin pamuk verimi üzerindeki etkileri, stresin şiddetine, süresine ve bitkinin maruz kaldığı gelişim dönemine bağlı olarak değişmektedir. Erken dönemde yaşanan soğuk stresi, bitki popülasyonunun azalmasına ve vejetatif büyümenin gerilemesine yol açarak dolaylı yoldan verim kayıplarına neden olmaktadır. Pamukta verim, bitkideki koza sayısı ve ağırlığı tarafından belirlenir (Heitholt, 1993). Koza ağırlığı ve koza boyutunun da sıcaklık stresi koşulları altında azaldığı, 40 °C'nin üzerindeki sıcaklıkların koza olgunlaşma süresinin kısalmasına ve normal sıcaklıklar altında geliştirilen kozalardan daha az ağırlığa sahip daha küçük boyutlu kozaların oluşumuna neden olduğu bildirilmektedir (Karademir vd., 2012). Çiçeklenme ve koza oluşumu dönemlerinde yaşanan düşük sıcaklıklar doğrudan koza sayısını ve koza ağırlığını azaltarak verim üzerinde kritik etkiler yaratmaktadır. Avustralya'da Luo vd. (2014) bir sıcaklık modelleme yaklaşımı önermiş ve düşük sıcaklıkların, gecikmiş büyüme mevsimi döneminde erken büyüme sırasında daha az zarar vereceğini; yüksek sıcaklığın ise pamuk bitkisinin büyümesi üzerinde, özellikle koza oluşumu aşamasında hızlandırılmış bitki gelişimi ile birlikte ciddi bir etkiye sahip olacağını ve bunun ancak yönetim seçenekleriyle karşılanabileceğini bulmuşlardır.

Soğuk stresinin pamuk lif kalitesi üzerindeki etkileri de göz ardı edilmemelidir. Düşük sıcaklıklar, lif uzaması ve kalınlaşması dönemlerinde selüloz biyosentezini yavaşlatarak lif uzunluğunun, mukavemetinin ve inceliğinin (mikronaire) olumsuz etkilenmesine neden olabilmektedir. Koza olgunlaşma süresinin soğuk koşullarda uzaması, liflerin tam olgunlaşamamasına ve kalite parametrelerinin düşmesine yol açmaktadır. Bununla birlikte, geç sezondaki soğuk stresi, liflerin erken olgunlaşmasını ve kurumasını tetikleyerek lif kalitesinde bozulmalara neden olabilmektedir. Gipson ve Ray (1969), daha yüksek ve daha düşük sıcaklık

limitlerinde lif indeksi, koza başına üretilen lif ve lif yüzdesinde azalma olduğunu, lif büyüme süresi ve uzama hızının çeşitler arasında ve çevresel faktörlerin değişmesiyle değişebildiğini vurgulamışlardır. Geç ekim nedeniyle azalan sıcaklıklar ve düşük ışık yoğunluğu, lif uzama oranlarının ve lif mukavemetinin azalmasına neden olmaktadır (Liu vd., 2015).

SONUÇ VE ÖNERİLER

Bu derleme, pamukta düşük sıcaklık stresinin çok boyutlu fizyolojik etkilerini kapsamlı bir şekilde ortaya koymaktadır. Düşük sıcaklık stresi, hücre zarı bütünlüğünün bozulmasından fotosentetik performansın düşmesine, oksidatif stresin artmasından ozmotik dengenin bozulmasına kadar geniş bir yelpazede fizyolojik hasara yol açmaktadır. Bitkiler bu strese karşı antioksidan savunma sistemlerinin güçlenmesi, ozmotik düzenleyici maddelerin birikimi, membran lipid bileşiminin yeniden düzenlenmesi ve hormonal sinyal yollarının aktivasyonu gibi çoklu savunma mekanizmalarını devreye sokmaktadır.

Gelecekte, pamukta soğuk toleransının iyileştirilmesine yönelik; soğuğa toleranslı gen kaynaklarının taranması ve ıslah programlarında kullanılması, CRISPR/Cas9 ve diğer gen düzenleme teknolojileriyle soğuk tolerans genlerinin düzenlenmesi, melatonin, salisilik asit ve brassinosteroidler gibi ekzojen biyostimülantların soğuk stres koşullarında etkinliklerinin değerlendirilmesi, soğuğa toleranslı ve duyarlı genotipler arasındaki fizyolojik ve moleküler farklılıkların omik teknolojilerle aydınlatılması ve iklim değişikliği senaryoları altında pamuk yetiştirme bölgelerinin yeniden değerlendirilmesi ve adaptasyon stratejilerinin geliştirilmesine yönelik araştırma alanlarına odaklanılması önerilmektedir. Ayrıca pamuk üretiminde düşük sıcaklığın olumsuz etkilerini minimize etmek amacıyla; uygun malçlama teknikleri gibi agronomik uygulamaların, spesifik bitki besleme programlarının ve biyoteknolojik müdahalelerin bir arada yürütüldüğü entegre bir yönetim stratejisinin benimsenmesi, sektörün geleceği açısından belirleyici olacaktır. Sonuç olarak, düşük sıcaklık stresi pamuk üretimi için önemli bir tehdit olmaya devam etmektedir. Bu stresin fizyolojik mekanizmalarının daha iyi anlaşılması, hem geleneksel ıslah yöntemleri hem de modern biyoteknolojik yaklaşımlarla soğuğa toleranslı pamuk çeşitlerinin geliştirilmesi ve sürdürülebilir pamuk üretiminin sağlanması açısından önem arz etmektedir.

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RENAL DAMAGE ASSOCIATED WITH OVARIAN REMNANT SYNDROME (ORS) AND STUMP PYOMETRA IN A BITCH

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Abstract

Ovarian remnant syndrome (ORS) is a complication that develops when functional ovarian tissue left within the abdominal cavity continues its hormonal activity after ovariohysterectomy. In cases where uterine tissue is not completely removed, stump pyometra may also accompany this condition. Indeed, although systemic effects have been described in cases where ORS and stump pyometra occur together, the number of reports detailing renal injury findings remains limited. The material of this case report consisted of a 4-year-old, 23-kg, Labrador bitch. Although the patient had undergone a spaying operation at 2 years of age, it was presented to the Department of Obstetrics and Gynaecology, Faculty of Veterinary Medicine, Hatay Mustafa Kemal University, with complaints of persistent estrus signs, foul-smelling brown-bloody vaginal discharge, anorexia, polydipsia, and polyuria. Hormonal analyses revealed a progesterone level of 8.40 ng/mL and an estradiol level of 34 pg/mL, findings that supported the presence of functional ovarian tissue after surgery and were considered in favor of an ORS diagnosis. Haematological examination showed leucocytosis ($28.30\times10^3/\mu L$) and neutrophilia ($23.20\times10^3/\mu L$), while biochemical analysis demonstrated elevated CRP (21.84 mg/L), suggesting an ongoing inflammatory uterine process. On abdominal ultrasonography, the presence of uterine tissue together with anechoic luminal content supported the preliminary diagnosis of stump pyometra. Renal ultrasonography demonstrated a kidney-to-aorta ratio of 5.95 and disruption of the corticomedullary distinction in favor of the cortex, indicating renal damage. In addition to these findings, elevated serum biochemical values of BUN (117 mg/dL), creatinine (2.76 mg/dL), phosphorus (6.79 mg/dL), and SDMA (22 µg/dL) suggested the presence of stump pyometra-associated renal damage in this case. Based on the combined evaluation of clinical, laboratory, and imaging findings, surgical intervention was planned with the preliminary diagnoses of ORS-associated stump pyometra and accompanying renal damage. During the operation, it was determined that only the proximal one-third of the uterine horns had been excised and that an incorrect partial hysterectomy had been performed during the previous surgery. The uterus showed an appearance compatible with cystic endometrial hyperplasia and pyometra. Adhesions resulting from the previous surgery were carefully dissected, and the remaining uterine tissue together with the ovaries were completely removed. In the postoperative period, broad-

spectrum antibiotics, anti-inflammatory therapy, and supportive treatment were administered. The patient recovered uneventfully. This case emphasizes that ORS and stump pyometra secondary to an improperly performed ovariohysterectomy may not remain limited to the genital system and may also lead to significant systemic involvement. Therefore, in supposedly spayed bitches with persistent estrus signs, a comprehensive diagnostic approach including hormonal, haematological, biochemical, abdominal, and renal ultrasonographic evaluations is of critical importance for establishing the correct diagnosis and guiding definitive treatment.

Keywords: Ovarian remnant syndrome, stump pyometra, renal damage, bitch

BİR KÖPEKTE OVARİAN REMNANT SENDROM (ORS) VE STUMP PYOMETRA İLİŞKİLİ RENAL HASAR

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Özet

Ovaryan remnant sendromu (ORS), ovariohisterektomi sonrası abdominal boşlukta bırakılan fonksiyonel ovaryum dokusunun hormonal aktivitesini sürdürmesi sonucu gelişen bir komplikasyondur. Bu tabloya, uterin dokunun tam olarak uzaklaştırılmadığı durumlarda stump pyometra da eşlik edebilmektedir. Nitekim ORS ve stump pyometranın birlikte görüldüğü olgularda sistemik etkiler tanımlanmış olmakla birlikte, böbrek hasarı bulgularının ayrıntılı olarak ortaya konduğu vaka sayısı sınırlıdır. Bu olgu sunumunun materyalini, 4 yaşında, 23 kg canlı ağırlığında, Labrador ırkı dişi bir köpek oluşturdu. Hasta, 2 yaşında kısırlaştırma operasyonu geçirmiş olmasına rağmen devam eden kızgınlık belirtileri, vajinadan gelen kötü kokulu kahverengi-kanlı akıntı, iştahsızlık, polidipsi ve poliüri şikâyetleriyle Hatay Mustafa Kemal Üniversitesi Veteriner Fakültesi Doğum ve Jinekoloji Kliniği'ne getirildi. Hormon analizlerinde progesteron düzeyinin 8.40 ng/mL, östradiol düzeyinin ise 34 pg/mL olarak belirlenmesi, operasyon sonrasında fonksiyonel ovaryum dokusunun varlığını destekleyerek ORS tanısı lehine değerlendirildi. Hematolojik incelemede saptanan lökositoz ($28.30\times10^3/\mu L$) ve nötrofili ($23.20\times10^3/\mu L$) ile biyokimyasal analizde belirlenen CRP yüksekliği (21.84 mg/L), devam eden inflamatuvar uterin süreci düşündürdü. Abdominal ultrasonografide uterin doku varlığı ile lümen içerisinde anekojen içerik saptanması, stump pyometra ön tanısını destekledi. Renal ultrasonografide böbrek/aorta oranının 5.95 olarak belirlenmesi ve kortikomedüller ayrımın korteks lehine bozulmuş olması, renal hasara işaret etti. Bu bulgulara ek olarak, serum biyokimyasında BUN (117 mg/dL), kreatinin (2.76 mg/dL), fosfor (6.79 mg/dL) ve SDMA (22 µg/dL) düzeylerinin yüksek bulunması, olguda stump pyometra ile ilişkili böbrek hasarı bulunduğunu düşündürdü. Klinik, laboratuvar ve görüntüleme bulgularının birlikte değerlendirilmesi sonucunda, ORS ile ilişkili stump pyometra ve eşlik eden böbrek hasarı ön tanılarıyla cerrahi müdahale planlandı. Operasyon sırasında, yalnızca cornu uterilerin proksimal üçte birlik kısmının eksize edildiği ve önceki cerrahide hatalı parsiyel histerektomi uygulandığı belirlendi. Uterusta kistik endometriyal hiperplazi ve pyometra ile uyumlu bir görünüm saptandı. Önceki operasyona bağlı gelişen adezyonlar dikkatli disseksiyonla ayrıldı ve kalan uterin doku ile ovaryumlar tamamen uzaklaştırıldı. Postoperatif dönemde geniş spektrumlu antibiyotik, antiinflamatuvar ve destekleyici tedavi uygulandı. Hasta sorunsuz olarak iyileşti. Bu olgu, hatalı ovariohisterektomiye bağlı ORS ve stump pyometranın yalnızca genital sistemle sınırlı kalmayıp önemli sistemik etkilenimlere de yol açabileceğini vurgulamaktadır. Bu nedenle, kısırlaştırıldığı bildirilen ancak östrus bulguları devam eden dişi köpeklerde, hormonal, hematolojik, biyokimyasal, abdominal ve renal ultrasonografik değerlendirmeleri içeren kapsamlı bir tanısal yaklaşım, doğru tanının konulması ve kesin tedavinin yönlendirilmesi açısından kritik öneme sahiptir.

Anahtar kelimeler: Ovarian remnant sendromu, stump pyometra, renal hasar, köpek

1. Introduction

Ovariectomy (OHE) is a surgical procedure commonly performed for birth control in female dogs and cats (Yılmaz et al., 2015). However, complications such as bleeding, incision-related issues, ureteral ligation, inflammatory response, and ovarian remnant syndrome (ORS) may occur. ORS is characterized by the presence of residual tissue resulting from incomplete removal of ovarian tissue during surgery and continued hormonal activity (Sontas et al., 2007). Recurrent estrus signs are observed in ORS cases, and this condition may predispose animals to stump pyometra, mammary neoplasms, and granulosa cell tumors (Bal et al., 2010; Zambelli et al., 2025). In ORS, which is reported to be more common in dogs, it is stated that residual tissue most frequently remains in this region due to the anatomical location of the right ovary (Case et al., 2020).

Pyometra in dogs is a significant reproductive disorder that typically develops during the diestrus phase after uterine contamination by bacteria from the vaginal microbiota, particularly affecting adult and elderly female dogs (Hagman et al., 2014). Although renal damage is commonly observed in female dogs with pyometra, its pathogenesis has not been fully elucidated. Renal failure developing during pyometra is considered one of the primary factors determining the prognosis of the disease. Therefore, investigating biomarkers that can predict the course of the disease and identify renal damage in its early stages is of great importance (De Loor et al., 2013; Pressler, 2015). The sepsis and toxemia that develop in pyometra suppress bone marrow function, leading to non-regenerative anemia, while sepsis resulting from the immune system's dysregulated response to infection causes life-threatening organ dysfunction. It has been reported that sepsis develops in approximately 60% of confirmed pyometra cases. Furthermore, acute kidney injury (AKI) occurs in approximately 12% of cases where sepsis develops, and fewer than 14% of these patients survive (Karlsson et al., 2012).

In cases of pyometra, renal dysfunction develops due to the combined effects of mechanisms such as endotoxemia, glomerular dysfunction, tubular damage, and reduced ADH response (Xavier et al., 2023). Hyperproteinemia and hyperglobulinemia may occur as a result of dehydration and antigenic stimulation, while blood urea nitrogen levels increase in prerenal uremia. When accompanied by urinary tract infection, elevations in urea, creatinine, and pancreatic amylase levels may be observed. A mild increase in liver enzymes may result from reduced hepatic perfusion due to sepsis and dehydration (Nak et al., 2004; Feldman and Nelson, 2004).

In light of this information, although OHE is routinely and widely performed, potential complications in the postoperative period must not be overlooked from a clinical perspective. In particular, ORS, due to the hormonal activity of residual ovarian tissue, may not be limited to recurrent estrus signs but can also lead to serious uterine stump infections, such as stump pyometra, and systemic complications. Therefore, early diagnosis of ORS, comprehensive evaluation of associated pathologies, and planning an appropriate surgical approach are of great importance. In this case report, a dog diagnosed with stump pyometra associated with ORS is discussed in detail, including hematobiochemical analyses, ultrasonographic findings, renal involvement, the surgical approach, and the postoperative clinical course.

2. Case Presentation

The subject of this case report was a 4-year-old female Labrador Retriever weighing 23 kg. The patient was brought to the Obstetrics and Gynecology Clinic at the Faculty of Veterinary Medicine, Hatay Mustafa Kemal University, with persistent signs of estrus despite being spayed, a foul-smelling, brown-tinged bloody vaginal discharge, loss of appetite, polydipsia, and polyuria.

According to the medical history provided by the owner, the dog was spayed at the shelter at the age of 2. Proestrus bleeding began approximately 10 days ago, and this bleeding, which was initially drop-like, quickly developed into a foul-smelling brownish-red discharge. It was reported that after the onset of proestrus bleeding, the animal showed a desire to mate, but the owner prevented this. Clinical findings suggested ovarian remnant syndrome (ORS).

Hematological examination revealed leukocytosis ($28.30\times10^3/\mu L$) and neutrophilia ($23.20\times10^3/\mu L$), while biochemical analysis showed elevated blood urea nitrogen (BUN; 117.00 mg/dL), creatinine (CRE; 2.76 mg/dL), phosphorus (P; 6.79 mg/dL), symmetric dimethylarginine (SDMA; 22.00 µg/dL), and C-reactive protein (CRP; 21.84 mg/L). Hormone analysis showed progesterone (P4) at 8.40 ng/mL and estradiol-17β (E2) at 34.00 pg/mL. The elevated progesterone level supported the preliminary diagnosis of stump pyometra.

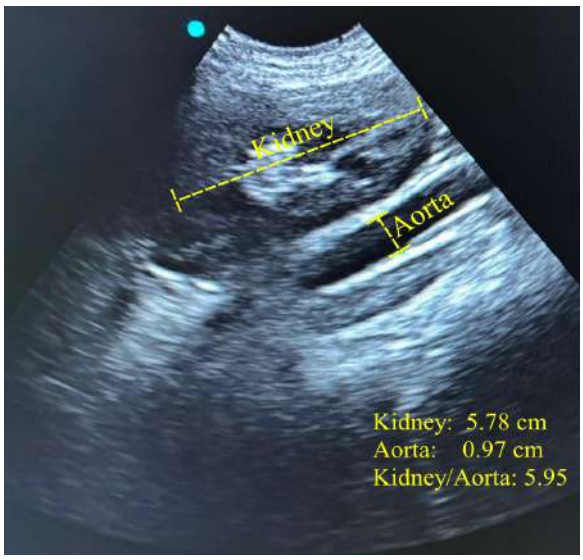
Table 1. Complete Blood Count (CBC), Biochemistry, and Hormone Analysis Results

PARAMETER	RESULT	UNIT	REFERENCE RATES		EVALUATION
WBC	28.30	/mm³	6,000	17,000	↑
Lym	10.50	%	10,50	30,000	↓
Lym	3.00	#	0,600	5,100	N
Mon	2.80	%	2,000	10,000	N
Mon	0.80	#	0,100	1,700	N
Neu	82.00	%	50,000	80,000	↑
Neu	23.20	#	3,000	13,600	↑
Eos	4.00	%	2,000	10,000	N
Eos	1.10	#	0,100	1,700	N
Bas	0.70	%	0,000	0,200	↑
RBC	7.60	/mm³	5,500	8,500	N
MCV	62.60	fL	58,000	73,000	N
Hct	48.10	%	35,000	55,000	N
MCH	17.80	Pg	20,000	25,000	N
MCHC	28.40	g/dl	28,000	40,000	N
RDW	10.70	ADET	8,000	12,000	N
Hb	13.70	g/dl	10,000	18,000	N
THR	346.00	/mm³	120,000	600,000	N
MPV	9.00	fL	5,000	12,000	N
PCV	0.30	%	0,000	0,200	↑
PDW	7,50	ADET	6,000	10,000	↑
BUN	117.00	mg/dL	7.00	27.00	↑
CRE	2.76	mg/dL	0.50	1.70	↑

P	6.79	mg/dL	2.50	6.00	↑
SDMA	22.00	µg/dL	0.00	14.00	↑
CRP	21.84	mg/L	0.00	10.00	↑
P_4	8.40	ng/mL	7.00	-	-
E_2	34.00	pg/mL	0.50	-	-

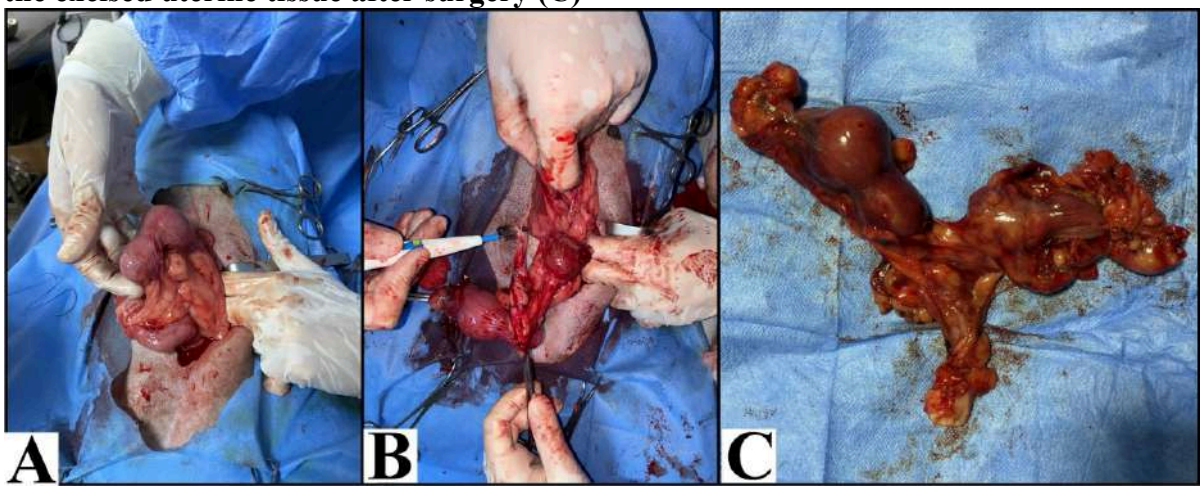
An abdominal ultrasound showed uterine tissue and anechoic content within the uterine lumen. Renal ultrasound revealed a kidney-to-aorta ratio of 5.95 and impaired corticomedullary distinction favoring the cortex, which were interpreted as indicators of renal damage (Figure 1). Based on a comprehensive evaluation of the medical history, clinical examination, complete blood count, biochemical analyses, and ultrasound findings, a diagnosis of ovarian remnant syndrome (ORS) and stump pyometra was established. After diagnosis, surgery was planned.

Figure 1. Transabdominal ultrasound image of the right kidney in this case



Xylazine (Sanalazin, Albafarma İlaç, Turkey), an alpha-2 adrenergic agonist with sedative and analgesic effects, was administered (1–2 mg/kg IM) for premedication. Ketamine (Keta-Kontrol, Doğa İlaç, Turkey) was used (10–20 mg/kg IM) for induction. Once an adequate depth of anesthesia was achieved, the patient was intubated and switched to inhalation anesthesia, with maintenance continued using isoflurane. Respiratory and cardiovascular parameters were monitored throughout the procedure. The patient was positioned in ventro-dorsal recumbency on the operating table. For surgical preparation, the abdominal area was shaved to ensure asepsis and antisepsis. A ventro-median approach was selected, and a routine ovariohysterectomy was performed. During the operation, it was noted that in the previous OHE procedure, only the proximal one-third of the uterine horns had been excised. The uterus showed findings consistent with cystic endometrial hyperplasia and pyometra (Figure 2). Adhesions from the previous surgery were carefully dissected and separated, and the remaining uterine tissue and ovaries were removed. The abdomen was then closed according to standard procedure.

Figure 2. Macroscopic view of the uterus during surgery (A and B); macroscopic view of the excised uterine tissue after surgery (C)



In the postoperative period, combined antibiotic therapy was administered to prevent secondary infection. Amoxicillin-clavulanic acid (Synulox, Zoetis, Turkey) (8.74 mg/kg SC) and enrofloxacin (Baytril-K, Bayer, Turkey) (5 mg/kg SC) were prescribed for this purpose. Meloxicam (Meloxicam, Bavet İlaç, Turkey) (0.2 mg/kg SC) was administered to control postoperative pain. The patient was monitored for postoperative complications and received fluid and electrolyte therapy. After the wound healed without complications, the sutures were removed on the 10th day, resulting in full recovery.

3. Discussion

ORS is a complication that may develop after ovariohysterectomy (OHE) or ovariectomy and is characterized by the presence of functional ovarian tissue that causes the onset of estrus signs. Stump pyometra is another complication that may occur following OHE (Demirel and Acar 2012). Although this condition is often attributed to inadequate surgical technique, retrospective studies have shown that in most cases, the initial surgery was performed by experienced veterinarians (Adin 2011). In most cases, residual ovarian tissue is found in the right ovarian pedicle, which is located deeper and more cranially due to its topographical position (de Sousa Oliveira et al. 2012). The most commonly reported clinical findings in ORS cases include behavioral changes, vulvar edema or swelling, and vaginal discharge, which is particularly noticeable in dogs (Adin 2011; de Sousa Oliveira et al. 2012). In the present case, the persistence of estrus signs despite a history of OHE, along with vulvar changes and vaginal discharge, was consistent with ORS cases reported in the literature.

It has been established that the belief that stump pyometra develops due to incomplete removal of the uterus is incorrect. Extensive studies in Europe have shown that ovariectomy alone is as effective as ovariohysterectomy in preventing pyometra (Adin, 2011). In another reported case, administration of tamoxifen, an estrogen receptor antagonist, for therapeutic purposes to a spayed dog diagnosed with sclerosing encapsulated peritonitis in which no residual ovarian tissue was detected resulted in stump pyometra (Ehrhardt et al., 2023).

The mechanism underlying the development of stump pyometra is the same as that of classic canine pyometra. The primary cause is repeated exposure of uterine tissue to the hormone progesterone. Progesterone is typically secreted by residual ovarian tissue remaining in the body; very rarely, it may result from exogenous hormone therapy. Consequently, stump pyometra is most often a complication resulting from ORS (Adin 2011). In the presented case, it is thought that the remaining ovarian tissue continued to function, producing estrogen and

progesterone, and that high progesterone levels may have created conditions conducive to the development of pyometra in the uterine stump tissue.

Assessing kidney function in cases of pyometra is clinically important. Traditionally, kidney disease is evaluated by increases in serum creatinine and blood urea nitrogen (BUN) levels. However, factors such as body condition, dehydration status, and diet can influence these parameters, and these values may remain within normal limits until more than 75% of kidney function is lost. This delay makes early diagnosis difficult. Symmetric dimethylarginine (SDMA) increases with a reduction of approximately 25% in glomerular filtration rate, making it a reliable biomarker for early-stage kidney damage (Matchimakul, 2018). In the present case, the SDMA level was 22 µg/dL, which is above the reference range (0–14 µg/dL) and indicates reduced kidney function and renal damage. Although the literature reports that most cases of stump pyometra are often accompanied by ORS (Demirel and Acar, 2012; Sonta et al., 2010), no specific study has directly demonstrated the renal damage associated with this condition. Therefore, it is believed that this case will significantly contribute to the literature by showing that stump pyometra can affect renal function and lead to renal damage.

4. Conclusion

The presented case shows that ORS should not be viewed solely as a complication limited to recurrent estrus symptoms after ovariohysterectomy (OHE); residual ovarian tissue may predispose dogs to stump pyometra due to ongoing hormonal activity. Stump pyometra is more than a local genital tract infection; it can significantly impact the patient's overall clinical condition by causing a systemic inflammatory response, hematobiochemical changes, and renal dysfunction. Therefore, in female dogs reported to have been spayed but showing signs of estrus, vulvar changes, or vaginal discharge, ORS should be included among the differential diagnoses. During diagnosis, a comprehensive approach should be taken, including hormonal evaluations, hematological and biochemical analyses, urinalysis, and imaging methods such as ultrasonography, rather than relying only on clinical findings. Surgical removal of residual ovarian tissue and infected uterine remnants is the primary treatment for successful management. However, careful monitoring of systemic inflammation and renal involvement during the perioperative period is essential for improving prognosis and reducing the risk of complications.

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ALEVİ-BEKTAŞİ GELENEĞİNDE NEFES VE DEYİŞ FORMLARI: TÜRK DİN MUSİKİSİ MERKEZLİ BİR İNCELEME VE YAPAY ZEKÂ DESTEKLİ KÜLTÜREL AKTARIM

NEFES AND DEYIS FORMS IN THE ALEVI-BEKTASHI TRADITION: A TURKISH RELIGIOUS MUSIC–CENTERED ANALYSIS AND AI-SUPPORTED CULTURAL TRANSMISSION

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ÖZET

Bu çalışma; Alevi-Bektaşi geleneğine ait iki özgün musiki formu olan nefes ve deyişi, Türk din musikisinin birer formu olma niteliğiyle çok boyutlu bir perspektiften ele almaktadır. Anadolu'nun kadim sentezi içinde biçimlenen Alevi-Bektaşi kültürü; inanç değerlerini, ahlâk öğretisini ve toplumsal belleğini yüzyıllar boyunca sözlü kültür ve musiki yoluyla aktarmış; bu süreçte nefes ve deyiş formları kimliğin musikal ifade araçlarına dönüşmüştür. Çalışmada öncelikle Aleviliğin ve Bektaşîliğin kısa tarihsel-kültürel arka planı aktarılmış; ardından nefes ve deyiş kavramları etimolojik ve kavramsal düzeyde tahlil edilmiştir. Nefes, tasavvuf geleneğinde Nefes-i Rahmânî anlayışıyla ilişkilendirilen ve ritüel bağlamda icra edilen besteli şiiri ifade ederken; deyiş, dinî, ahlâkî ve toplumsal içerikleri kapsayan daha geniş bir söyleyiş alanına karşılık gelir. Türk din musikisi içindeki konumları makamsal yapı, usûl repertuvarı, icra tavrı ve ritüel bağlam üzerinden değerlendirilmiş; yirmi yedi farklı makam ve Bektaşi Devr-i Revânı ile Bektaşi Raksanı gibi özgün usûller tespit edilmiştir. Örnekler bölümünde "Zâhid Bizi Tan Eyleme", "Haydar Haydar", "Bu Yıl Bu Dağların Karı Erimez" ve "Şâh-ı Merdânın Avazı" gibi popüler eserler; anlam katmanları, makamsal-usûlî yapıları ve modern yorumcuları çerçevesinde incelenmiştir. Son bölümde üretici yapay zekâ teknolojilerinin bu repertuvarın belgelenmesi, çözümlenmesi ve aktarımındaki olası katkıları ile etik sınırları tartışılmıştır. Sonuç olarak nefes ve deyişlerin Türk din musikisi içinde marjinal değil; kurucu ve genişleyen bir form alanı oluşturduğu, mirasın geleceğe taşınmasında geleneksel meşk ile dijital araçların birlikte değerlendirilmesi gerektiği ortaya konulmuştur.

Anahtar Kelimeler: Türk Din Musikisi, Alevi-Bektaşi musikisi, nefes, deyiş, yapay zekâ.

ABSTRACT

This study examines nefes and deyiş—two distinctive musical forms of the Alevi-Bektashi tradition—as autonomous forms within Turkish religious music. Shaped within Anatolia's syncretic heritage, Alevi-Bektashi culture has transmitted its values of faith, ethics, and collective memory for centuries primarily through oral culture and music; in this process, nefes and deyiş have become the principal musical expressions of that identity. The paper first offers a concise historical and cultural background of Alevism and Bektashism, then analyses the etymological and conceptual dimensions of both terms. Nefes denotes a composed devotional poem rooted in the Sufi concept of Nefes-i Rahmânî and performed within ritual settings, while deyiş encompasses a broader repertoire of religious, ethical, and social verse. Their position within Turkish religious music is evaluated through modal structure, rhythmic repertoire, performance practice, and ritual context. Analysis of eighty-seven notated Bektashi nefes reveals twenty-seven distinct maqams—led by Hüseynî, Uşşak, Hicaz, Sabâ, and Segâh—alongside tradition-specific rhythmic cycles such as Bektaşi Devr-i Revânı and Bektaşi Raksanı. A central section presents close readings of widely performed works—"Zâhid Bizi Tan Eyleme", "Haydar Haydar", "Bu Yıl Bu Dağların Karı Erimez", and "Şâh-ı Merdânın Avazı"—examining their lyrical layers, modal-rhythmic structures, and contemporary interpreters. The concluding section discusses how generative AI technologies may contribute ethically and effectively to the documentation, analysis, and transmission of this repertoire. The study concludes that nefes and deyiş constitute not a marginal but a foundational and continually expanding form field within Turkish religious music, and that safeguarding this heritage requires a balanced integration of traditional meşk and digital tools.

Keywords: *Turkish Religious Music, Alevi-Bektashi music, nefes, deyiş, artificial intelligence.*

1. GİRİŞ

Türk din musikisi literatürü uzun yıllar boyunca büyük ölçüde cami musikisi ve klasik tekke musikisi ekseninde şekillenmiş; ilâhî, tevşih, durak, na't, mersiye, mevlid ve zikir formu gibi başlıklar bu alanın temel formları olarak öne çıkarılmıştır. Buna karşılık Alevi-Bektaşi musiki geleneği, kimi çalışmalarda halk müziği, kimi çalışmalarda tekke musikisi, kimi zaman da folklor ya da sözlü kültür başlığı altında ele alınmış; dolayısıyla bu geleneğin kendi iç form mantığı çoğu kez ikincil planda kalmıştır. Oysa Bektaşi nefesleri ve Alevi deyişleri yalnızca şiir metinleri veya melodik ezgiler topluluğu değil; inanç sisteminin bizzat ses, söz, hafıza ve ritüel yoluyla kurduğu bir tecrübe alanıdır.

Bu çerçevede mevcut bildirinin temel sorusu şudur: Nefes ve deyişler hangi gerekçelerle Türk din musikisinin müstakil formları arasında değerlendirilmelidir? Temel tezimiz ise şudur: Nefes ve deyişler; makam, usûl, saz tavrı, icra çevresi ve ritüel meşruiyet unsurlarıyla belirlenmiş, inancın sesli bedenini meydana getiren dinî-musikî yapılardır. Bu yüzden söz konusu eserler, yalnızca halk edebiyatının türleri olarak değil, din musikisinin canlı ve işlevsel formları olarak kavranmalıdır.[1]

Bildirinin yapısı altı eksen üzerine kurulmuştur: (i) Aleviliğin ve Bektaşîliğin kısa tarihsel-kültürel arka planı; (ii) nefes ve deyiş kavramlarının etimolojik ve formel tahlili; (iii) bu formların Türk din musikisi içindeki konumu; (iv) makam, usûl ve icra tavrı bakımından müzikal yapı; (v) cem ve muhabbet bağlamında ritüel işlev ile popüler örnekler üzerinden eser merkezli okumalar; (vi) üretici yapay zekâ uygulamalarının bu repertuvarın belgelenmesi, analizi ve aktarımındaki rolü.

2. ARAŞTIRMA VE BULGULAR

2.1. ALEVİLİK VE BEKTAŞÎLİĞİN KISA TARİHSEL-KÜLTÜREL ARKA PLANI

Alevilik; itikadî, tasavvufî ve kültürel düzlemlerde Hz. Ali ve Ehl-i Beyt'e bağlılığı esas alan bir inanç ve kültür dünyasının adıdır. "Alevî" sözcüğü Arapça "Alî" isminden türemiş olup "Ali'ye mensup, Ali'ye bağlı" anlamını taşır.[2]

Bektaşîlik ise XIII. yüzyıldan itibaren Anadolu'da teşekkül eden bir tarikattır. Hacı Bektâş-ı Velî'nin manevî mirası etrafında biçimlenen bu yol, Yesevîlik, Ahîlik, abdal ve kalenderî gelenekleri ile çeşitli halk Müslümanlığı renklerini sentezleyerek kendine özgü bir öğreti, edebiyat ve musiki dünyası kurmuştur. Anadolu Aleviliği bu zenginliğin önemli bir unsurudur; bununla birlikte şehirli Bektaşîlik ile köy ve kasaba Aleviliği arasında tarih boyunca kültürel düzlemde belirli farklılıklar oluşmuştur.

Tekkelerin ve zaviyelerin kapatılması, 30 Kasım 1925 tarihinde yürürlüğe giren 677 sayılı Kanun çerçevesinde gerçekleştirilmiştir. Bu düzenleme; Türkiye Cumhuriyeti'nin modernleşme ve ulusal birleşme hedefleri doğrultusunda hayata geçirilen kapsamlı reformların bir parçasıdır.

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[1] Yavuz Şen, "Bektaşi Nefesleri Üzerine Makamsal Bir İnceleme", *Bilig* 85 (2018), 211-213.

[2] Adem Çaylak - Cansu Kaymal, "Alevilikte Muhalif Dil ve Söylem: Alevî Türkü ve Deyişleri Üzerine Bir Analiz", KAÜİİBFD 11/22 (2020), 1079.

Yeniçeri Ocağı ile Bektaşilik arasındaki tarihsel bağ, 1826 yılında Yeniçeri Ocağı'nın feshiyle birlikte Bektaşi tekkelerinin de kapatılmasına zemin hazırlamıştır. Bu süreç, Bektaşilik kurumunun örgütsel biçimde gerilemesine yol açmış; ancak inancın sözlü kültür yoluyla sürdürülmesini engelleyememiştir.

Tarihsel süreç içerisinde söz konusu topluluklar çeşitli dönemlerde toplumsal baskı ve dışlanma deneyimleriyle karşılaşmış; bu deneyim, dayanışmacı ve sözlü kültür yoluyla beslenen bir yapının oluşmasına zemin hazırlamıştır.[3] Bu süreçlerin doğurduğu kültürel hassasiyet, nefes ve deyişlerde belirgin biçimde duyulan inanç bağlılığı, sabır, mâtem ve ahlakî öğüt temalarının zenginleşmesini sağlamıştır.

Antropolojik perspektiften bakıldığında bu geleneğin köklerinin Orta Asya Türk inançları, Şamanist ritüel pratikler ve İslâmî tasavvuf tecrübesi arasındaki tarihsel kesişimde aranması gerekmektedir.[4] Saz-söz birlikteliğine dayalı musiki anlayışı, kopuzdan bağlamaya uzanan çalgı geleneği ve şair-bilge figürünün merkezî konumu, bu sentezin somut izleridir.

Anadolu'nun bu çoğul kültürü, Pir Sultan Abdal, Kaygusuz Abdal, Kul Himmet, Yedi Ulu Ozan ve Yunus Emre gibi isimlerin şiir mirası ile beslenmiş; XIX-XX. yüzyıllarda Sıtkı Baba, Veliyettin Çelebi (Hürremî), Edib Harabî ve Âşık Veysel, Âşık Davut Sulari, Feyzullah Çınar ve Ali Ekber Çiçek gibi temsilcilerle yaşayan bir tedrise dönüşmüştür.

Anadolu'nun yanı sıra bu repertuvar Trakya, Batı Trakya, Makedonya, Bulgaristan ve Arnavutluk gibi geniş bir Balkan coğrafyasında da varlığını sürdürmektedir; bu durum nefes ve deyiş geleneğini sınır-aşan bir Türk din musikisi mirası olarak konumlandırmaktadır.[5]

2.2. NEFES VE DEYİŞ: ETİMOLOJİK KÖKEN VE KAVRAMSAL TAHLİL

2.2.1. Nefes Kelimesinin Sözlük ve Tasavvufî Anlamı

Arapça n-f-s kökünden gelen nefes kelimesi, lügat anlamı itibariyle "soluk, soluma, hayatın canlanması" demektir. Klasik Arap sözlükçülüğünün temel eserleri olan Halîl b. Ahmed'in *Kitabu'l-Ayn*'ı ve İbn Düreyd'in *Cemheretu'l-luğa*'sı bu kökten "canlılık, dinlenme, ferahlık ve süre" gibi anlamlar türetmiştir.[6]

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[3] Mehmet Eröz, Türkiye'de Alevîlik ve Bektâşîlik (Ankara: Kültür Bakanlığı Yayınları, 1990), 312-323.

[4] Ahmet Yaşar Ocak, Alevî ve Bektaşî İnançlarının İslâm Öncesi Temelleri (İstanbul: İletişim Yayınları, 2000), 162-165.

[5] Çaylak - Kaymal, "Alevilikte Muhalif Dil ve Söylem", 1075-1106.

[6] Mesut Yiğit, "Tasavvuf Müziğinde Nefes: Nefes-i Rahmânî'den Müzikal İcraya", Yegâh Musicology Journal 8/4 (2025), 4086-4087.

Nefes, Türk din musikisi içerisinde özellikle Alevî-Bektaşî geleneğe ait olan; tasavvufî düşünceyi, vahdet-i vücûd anlayışını ve insan-ı kâmil telakkisini şiir ve musiki birlikteliğiyle ifade eden sözlü-müzikal bir formdur. İçerik bakımından didaktik, irşad edici ve sembolik bir dil kullanır; Hak, Muhammed, Ali eksenli inanç sistematiğini merkeze alır. İcra bakımından çoğunlukla bağlama eşliğinde, belirli makam ve usul kalıpları içerisinde serbestlik gösterebilen bir yapı arz eder. Nefesler, ritüel bağlamda özellikle cem ayinlerinde zakir tarafından icra edilerek hem ibadet pratiğinin hem sözlü kültürel aktarımın temel araçlarından biri işlevini görür.

Tasavvuf düşüncesinde nefes; bedensel bir solumayı aşan metafizik bir işarete dönüşür. Süleyman Uludağ'ın *Tasavvuf Terimleri Sözlüğü*'nde nefes; "gaybın incelikleriyle kalpleri rahatlatan bir latîfe" ve "Hakk'ın rüzgârından bir esinti" olarak tanımlanır.[7] Muhyiddin İbnü'l-Arabî'nin Nefes-i Rahmânî öğretisi, varlığın her an bu ilâhî nefesle yeniden tecellî ettiğini ileri sürer.

Bektaşîlik özelinde ise nefes; Bektaşi şairleri tarafından söylenmiş ve Bektaşi tekkelerinde okunmak üzere çeşitli makam ve usûllerde bestelenmiş manzum eser anlamına gelir. Hece ve aruz vezinleriyle yazılmış olan bu şiirler; Allah sevgisi, Hz. Muhammed ve Hz. Ali'ye bağlılık, Ehl-i Beyt'e ve Yedi Ulu Ozan'a saygı, On İki İmam, Kerbelâ matemi, mi'râc, kâinatın yaratılışı, insan-ı kâmil ve ahlâkî öğretiler gibi temaları işler.

2.2.2. Deyiş Kavramı ve Nefesle İlişkisi

Türkçe "demek" fiilinden türeyen "deyiş" sözcüğü, Alevi-Bektaşi geleneğinde özel bir teknik kullanım kazanmıştır. Burada deyiş; bağlama eşliğinde, çoğunlukla cem ve muhabbet bağlamında icra edilen, dinî-tasavvufî, ahlâkî, didaktik ya da toplumsal içerikli manzum eserleri kapsayan geniş bir alanı ifade eder. Literatür dikkatle okunduğunda nefes ile deyiş arasında belirli bir anlam farkı oluştuğu görülür: Deyiş, daha geniş bir şiir ve söyleyiş alanını ifade ederken; nefes, daha belirgin biçimde bestelenmiş ve ritüel bağlamda işlev kazanan, dinî-musikî bir form olarak öne çıkar.[8]

Hacıbektaş yöresinde icra edilen deyişler üzerine yapılan saha çalışmaları, deyişlerin sadece dinî şiirler olmadığını; inanç, ahlâk ve hayat felsefesinin yanı sıra toplumsal mücadelelerin de bir ifadesi hâline geldiğini göstermektedir.[9] Ali Ekber Çiçek'in repertuvarına ait dört deyiş üzerinde yapılan

[7] Süleyman Uludağ, Tasavvuf Terimleri Sözlüğü (İstanbul: Kabalcı Yayınevi, 2005), 302.

[8] Refik Engin - Tazegül Demir, "Kızıldeli Süreklerinde Okunan Nefesler", Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 53 (2010), 411-412.

[9] Emre Üstün - Burcu Özer, "Hacıbektaş İlçesinde İcra Edilen Alevi Deyişlerinin Müzikal, Kültürel Yapıları ve Anlam Dünyası Üzerine Bir İnceleme", Yegâh Musicology Journal 9/1 (2026), 150-169.

kültürel, sözel ve müzikal analiz, deyişlerin çok katmanlı bir form olarak ele alınması gerektiğini ortaya koymaktadır.[10]

Sonuç olarak nefes ve deyiş; aynı geleneğin iki farklı, fakat birbirini tamamlayan kavramı olarak değerlendirilebilir. Deyiş, geniş bir söyleyiş havzasına atıfta bulunurken; nefes, bu havzanın ritüel meşruiyet kazanmış ve dinî-musikî bir kimliğe bürünmüş özgün katmanını imler. Bu nedenle her nefes aynı zamanda bir deyiştir; ancak her deyiş zorunlu olarak nefes değildir.

2.3. TÜRK DİN MUSİKİSİ İÇİNDE NEFES VE DEYİŞ

2.3.1. Bir Form Olmanın Kıstasları

Türk din musikisinde bir eser veya repertuvarı "form" olarak değerlendirebilmek için yalnızca dinî içerik yeterli değildir. Formun ritüel işlevi, icra çevresi, meşruiyet zemini, müzikal dili (makam ve usûl), icra tavrı ve toplum hafızasındaki yeri birlikte ele alınmak durumundadır. Bu ölçütler uygulandığında nefes ve deyişlerin Türk din musikisinin müstakil formlarından biri olduğu açıkça görülür.

Birinci ölçüt işlevselliktir. Nefes ve deyişler cem içinde belirli anlarda, on iki hizmet sırasıyla ilişkili olarak okunur. Cem dışında muhabbet meclisleri ve dardan indirme erkânı gibi özel ritüel zamanlarda da işlevseldirler.[11]

İkinci ölçüt meşruiyettir. Nefesler topluluk tarafından sıradan türkü olarak değil; erkânın parçası olarak kabul edilir ve cem içinde belirli protokollerle icra edilir. Üçüncü ölçüt müzikal kurallılıktır: Nefesler makam, usûl ve icra tavrı bakımından tanımlanabilir bir yapıya sahiptir. Dördüncüsü, saz-söz birlikteliğinin inançla kurduğu sıkı bağdır; bağlama, hem maddî hem manevî düzlemde kutsal bir aracılık üstlenir. Beşincisi, repertuvarın anonim niteliğine rağmen bestelerin uzun zaman dilimleri içinde tanınabilir tavırlarla aktarılmasıdır.

2.3.2. Diğer Tekke Musikisi Formlarıyla İlişki

Nefesler; Rifâîlik, Kâdirîlik ve Halvetîlik gibi Sünnî tarikat musikilerindeki ilâhîlerden üslûp, konu, melodi karakteri ve az da olsa usûl bakımından ayrılır. Nefesler, beste olarak daha ziyade halk musikisinin etkisi altında kalmıştır.[12]

Bu farklılığa rağmen Mevlevî âyinleri ile Bektaşî nefesleri arasında müzikal söz dağarcığı, makam tercihleri ve âşık musikisi köprüsü üzerinden çeşitli yakınlıklar mevcuttur. Bektaşi musikisi, klasik Türk müziği ile âşık geleneği ve halk musikisi arasında önemli bir köprü işlevi görmektedir.

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[10] Sedat Tamay, "Ali Ekber Çiçek'e Ait Deyiş Türünde Dört Eserin Kültürel, Sözel ve Müzikal Analizi", Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 93 (2020), 207-221.

[11] Mustafa Öcal - Mehmet Can Pelikoğlu, "Samsun Canlar Derneğinde Yaşatılan Alevi-Bektaşi Kültürü, Cem Ritüelleri ve Müzik Pratikleri", Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 111 (2024), 17-39.

[12] Nuri Özcan, "Bektâşî Mûsikisi", TDV İslâm Ansiklopedisi (İstanbul: TDV Yayınları, 1992), 5/371-372.

2.4. MÜZİKAL YAPI: MAKAM, USÛL VE İCRA TAVRI

2.4.1. Makam Repertuvarı

İstanbul Konservatuvarı Tasnif Heyeti tarafından 1933 yılında notaya alınan 87 Bektaşi nefesi üzerinde yapılan kapsamlı analiz, bu repertuvarda yirmi yedi farklı makamın kullanıldığını ortaya koymaktadır.[13]

En çok tercih edilen makamlar sıklık sırasına göre şu şekildedir: Hüseynî (15 eser), Uşşak (12), Hicaz (6), Sabâ (6), Segâh (6), Eviç Hüzî (6), Hüzzam (5), Pencügâh (5), Rast (3) ve Gerdâniye (3). Bunların yanında Karcığar, Tâhir, Muhayyer, Arabân, Acem, Acemkürdî, Bayatî-Arabân, Bûselik, Eviç, Hicâzî Uşşak, Hicâzkâr, Mâhûr, Neveser, Nihâvend, Rast Mâye, Rehâvî ve Uzzâl gibi makamlar da repertuvarda yerini almaktadır. Bu çeşitlilik, klasik Türk müziği makam birikiminin neredeyse tamamı ile temas eden bir derinliğe işaret etmektedir.

Hicaz ailesinde yapılan ayrıntılı analizde, Hümâyûn karakterli seyirlerin baskın olduğu, Nim Hicaz ve Dik Kürdî perdelerinin sıkça asma kalış noktası olarak işlev gördüğü tespit edilmiştir.[14]

2.4.2. Usûl ve Ritmik Yapı

Bektaşi nefeslerinin usûl repertuvarı son derece zengindir. En çok kullanılan usûl Düyek'tir (8/8). Onu Yürük Semâî (6/4), Sofyan (4/4), Aksak (9/8), Devr-i Hindî (7/8) ve Curcuna (10/8) izler.[15]

Bektaşi musikisinin en özgün katkısı, bu repertuvara mahsus üç usûldür: Bektaşi Devr-i Revânı (13 zamanlı, dokuz vuruşlu), Bektaşi Raksanı (15 zamanlı) ve Bektaşi Raksı (16 zamanlı). Bunlardan Bektaşi Devr-i Revânı, bir Aksak ile bir Sofyan'ın birleşmesinden meydana gelmiş; daha çok Bektaşi musikisinde ve nefeslerde kullanıldığı için bu adı almıştır.[16]

Bektaşi Raksanı, klasik Türk müziğinde kullanılan Raksan'dan farklı kuvvetli vuruş yapısıyla ayrılır: Klasik Raksan'da kuvvetli vuruşlar 1., 4. ve 9. zamanlardayken; Bektaşi Raksanı'nda 1., 6. ve 11. zamanlardadır. Bu fark, semah ritüelinin bedensel akışıyla doğrudan ilişkilidir. Yaltırık ise nefesleri usûl bakımından üç temel grupta sınıflandırır: usûlsüz uzun hava tipi nefesler; ağır usûllerle söylenen "oturak" nefesler; ve yürük usûllerle söylenen "şahlama" veya "semah nefesleri".

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[13] Gülçin Yahya Kaçar, "Bektaşi Nefeslerindeki Melodik ve Ritmik Özellikler", Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 55 (2010), 222-225.

[14] Şen, "Bektaşi Nefesleri Üzerine Makamsal Bir İnceleme", 215-220.

[15] Ahmet Hakkı Turabi - Süleyman Tuna, "Tahtacı Türkmenlerinde Nefes: Notasyon ve Müzikal Yapı Araştırması", Çukurova Üniversitesi İlahiyat Fakültesi Dergisi 25/2 (2025), 68-88.

[16] Nuri Özcan, "Bektâşî Devr-i Revânı", TDV İslâm Ansiklopedisi (İstanbul: TDV Yayınları, 1992), 5/371.

2.4.3. Saz, İcracı ve Tavır

Bektaşi musikisinde temel saz bağlamadır. Bağlama, Alevi-Bektaşi geleneğinde yalnızca bir çalgı değil; kutsal bir nesne olarak görülmektedir. Gövdesi Hz. Ali ile, sapı Zülfikâr ile, telleri ve perdeleri ise On İki İmam ile sembolik olarak ilişkilendirilmiştir; bu nedenle bağlamaya "telli Kur'an" denildiği de görülür.

Nefesleri ve deyişleri icra eden kişiye bölgeye göre zâkir, âşık, sâzende, gûyende veya güverde adı verilir. Zâkirin ses tavrı, nefesin karakterini belirleyen başlıca etkenler arasındadır.[17]

2.5. RİTÜEL BAĞLAM: CEM, MUHABBET VE HAKK'A YÜRÜME ERKÂNI

2.5.1. Cem Ritüelinde Nefes ve Deyişin Yeri

Cem; Alevi-Bektaşi geleneğinde inanç, ahlâk ve toplumsal birliğin yeniden üretildiği temel ritüeldir. Kadın ve erkek canların birlikte katıldığı bu törende musiki, kutsal söz ile topluluk arasındaki bağı kuran ana araçtır.[18]

Cem boyunca on iki hizmet sırasıyla yürütülür; bunların büyük çoğunluğunda nefes, duvâz imam, mersiye, mi'râclama ve semah müzikal akışın ayrılmaz bileşenleri olarak yerini alır. Semah, müziğin ve bedenin ritüel olarak buluştuğu ânı temsil eder. Semahta seslendirilen yürük usûllü nefeslere "şahlama" veya doğrudan "semah nefesi" adı verilir.

2.5.2. Mistik Boyut ve Manevî İşlev

Hakk'a yürüme erkânında müziğin yeri ve önemi üzerine yapılan çalışmalar, ölüm nefeslerinin Alevi-Bektaşi toplumunda ölüm algısının ayrılmaz bir parçası olduğunu ortaya koymaktadır.[19]

Eskişehir Seyitgazi-Arslanbeyli köyünde tespit edilen "dar nefes" örnekleri, "Geldi vedalaştı bir zülfü siyah" ve "Fırsat elde iken bir amel kazan" gibi metinlerin dardan indirme cemlerinde okunduğunu göstermektedir.[20]

2.6. ÖRNEK ESERLER ÜZERİNDEN OKUMALAR

2.6.1. "Zahid Bizi Tan Eyleme" – Bezcizade Mehmed Muhyiddin

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[17] Turgay Akdağoğlu, “Alevilikte Müzik Yoluyla İnanç İfade Biçimleri: ‘Nefes ve Semah’ Örneği”, Yegâh Musicology Journal 8/2 (2025), 555-558.

[18] Mustafa Öcal - Mehmet Can Pelikoğlu, “Samsun Canlar Derneğinde Yaşatılan Alevi-Bektaşi Kültürü, Cem Ritüelleri ve Müzik Pratikleri”, Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 111 (2024), 17-39.

[19] Yusuf Benli, “Alevî-Bektâşî Öğretisinde Hakk’a Yürüme Erkânında Müzik”, Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 91 (2019), 174-184.

[20] Pelin Demirçe Altıntaş - Nevzat Erol, “Eskişehir İli Seyitgazi İlçesine Bağlı Arslanbeyli Köyünde Nefes Formunda Eserler: Dar Nefes Örneği”, Motif Akademi Halkbilimi Dergisi 16/43 (2023), 1237-1250.

Edebî mahlas olarak "Muhyî" imzasını taşıyan bu eser; yüzyıllar boyunca farklı tasavvufî çevrelerce paylaşılmış ve günümüzde de Bektaşi nefesi olarak yaygın biçimde icra edilmektedir. Abdülbâki Gölpınarlı, *Melamilik ve Melamîler* adlı eserinde bu nefesin Hamzevîlerin idama götürülürken topluca okuduğu rivayetini aktarır.[21]

"Zâhid" sözcüğü, dinin zâhirî kaidelerine bağlı fakat manevî derinlikten uzak kişiyi imler. "Tan eyleme" ifadesi "ayıplama, kınama" anlamına gelir. Eserin açılış cümlesi şu sitemi taşır: "Ey zâhid, bizi sırf zâhirden bakarak ayıplama; bizim de dilimiz Allah'ı zikretmektedir." Eser bugün Erkan Oğur ve İsmail Hakkı Demircioğlu'nun akustik kaydı ve "Muhteşem Yüzyıl" televisyon dizisindeki kullanımıyla geniş kitlelere ulaşmıştır.[22]

2.6.2. "Haydar Haydar" – Kul Nesîmî

Asıl güftesi "Kime ne" redifli bir nefes olan bu eser, Türk din musikisi tarihinin en uzun ömürlü dinî-popüler taşıyıcılarından biridir. Cömert'in çalışması, eserin tekkelerden plak kültürüne, oradan klasik, halk, pop ve arabesk mecralarına uzanan asırlık yolculuğunu ayrıntılı biçimde belgelemektedir.[23]

Eserin Ali Ekber Çiçek tarafından yapılan icrası, "Haydar Haydar" adıyla anılan tipik biçimin oluşumunda belirleyici bir rol oynamıştır. Müzikal olarak Nikrîz makamında olan eser; "Kırkların ceminde dara düş oldum / Kırkların ceminde Haydar Haydar" mısraındaki nidâsıyla ritüel kimliğini en güçlü şekilde duyurur.

2.6.3. "Bu Yıl Bu Dağların Karı Erimez" – Pir Sultan Abdal / Feyzullah Çınar

Pir Sultan Abdal'a atfedilen ve Feyzullah Çınar icrasıyla bütün Türkiye'ye yayılan bu eser, hem mevsim mecazı hem de toplumsal taşlama kapsamında çok katmanlı bir yapı sunar.[24] Mirzaoğlu'nun gösterdiği üzere, "bâd-ı sabâ" motifi Türk şiirinde sevgilinin haberini taşıyan kutsal bir esinti olarak işlerken; bu nefeste rüzgârın "bozuk bozuk" esmesi, baharın gecikmesini ve Türkmen aşiretlerinin yaylaya göç düzeninin bozulmasını anlatır.

2.6.4. "Şah-ı Merdanın Avazı" – Anonim, Acemkürdî Makamı

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[21] Abdülbâki Gölpınarlı, Melamilik ve Melamîler (İstanbul: Gri Yayınları, 1992), 67-69.

[22] Murat Akkuş - Ceren Aksoy Sugiyama, “Popülerleşen Alevi Deyişlerinde Anlamı Yakalama ve Doğasına Dokunma Tartışmaları”, Antropoloji 39 (2020), 87-97.

[23] Eray Cömert, “Kul Nesîmî’nin ‘Kime Ne’ Redifli Meşhur Nefesi: Haydar Haydar’ın Tekkelerden Sahnelere Uzanan Asırlık Yolculuğu”, ODÜ Sosyal Bilimler Araştırmaları Dergisi 13/1 (2023), 115-158.

[24] F. Gülay Mirzaoğlu, “Alevî-Bektâşî Şiirinde Bâd-ı Sabâ Motifi”, Türk Kültürü ve Hacı Bektaş Velî Araştırma Dergisi 61 (2012), 109-130.

Acemkürdî makamında bestelenmiş ve Bektaşi Raksanı usûlü ile vurulan "Şâh-ı Merdânın avazı turna derler bir kuştadır" nefesi, Bektaşi musikisinin kendine has usûl yapısının en iyi tanındığı örneklerden biridir.[25]

Burada turna sembolü, Hz. Ali'nin sesinin Anadolu kuşunda tezahür ettiğine dair Alevi-Bektaşi mitolojisinin çekirdek imgelerinden birine dayanır. Acemkürdî makamının renkleri ile Raksan usûlünün ritmik hareketi arasındaki gerilim, hem bireysel ifadeyi hem ritüel coşkuyu mümkün kılar. Bunlara ek olarak çağdaş repertuvarda "Dostun Bahçesine Girdim Bu Gece" (Âşık Veysel), "Telli Turnam" ve "Erenlerin Cemine" gibi parçalar da nefes ve deyiş geleneğinin bugünkü canlılığını sergileyen popüler örnekler arasındadır.

2.7. POPÜLERLEŞME, BAĞLAM VE OTANTİKLİK

Nefes ve deyişlerin son yarım yüzyılda tekke ve cem ortamından sahneye, plaktan dijital platforma uzanan yolculuğu, repertuvarın görünürlüğünü artırırken aynı zamanda anlam ağırlığını da yer değiştirmiştir.[26]

Bu süreçte iki tür dönüşümden söz etmek mümkündür: geleneğin kendi içinde gerçekleşen doğal varyantlaşma; ve piyasa mantığının etkisiyle ortaya çıkan bağlam kaybı. Akademik bir tutum, bu iki süreci ikili bir "bozuldu/bozulmadı" yargısı yerine, anlam yer değişimini soğukkanlılıkla okuyan bir bağlam sosyolojisi içinde değerlendirmelidir.

2.8. YAPAY ZEKÂ DESTEKLİ KÜLTÜREL AKTARIM

2.8.1. Üretici Yapay Zekâ ve Yeni İmkânlar

Son yıllarda Suno, Udio, MusicGen ve folk-rnn gibi metin-müzik dönüşümü yapabilen üretici yapay zekâ modelleri, küresel ölçekte hızla yaygınlaşmıştır.[27] Nefes ve deyiş repertuvarı bağlamında bu teknolojiler; (i) dijital arşivleme ve tasnif, (ii) otomatik makam tanıma ve nota transkripsiyonu, (iii) eğitim ve aktarım düzlemlerinde önemli imkânlar sunmaktadır.

2.8.2. Klasik İcraların Yeniden Üretimi ve Popülere Katkı

Yapay zekâ müzik araçları, klasik nefes ve deyiş icralarını yeni dinleyici beklentileriyle uyumlu düzenlemelere dönüştürebilmektedir. Bu yeniden üretim süreci üç düzlemde olumlu katkı yapmaktadır:

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[25] Gülçin Yahya Kaçar, "Bektaşi Nefeslerindeki Melodik ve Ritmik Özellikler", Türk Kültürü ve Hacı Bektaş Veli Araştırma Dergisi 55 (2010), 228-229; Nuri Özcan, "Bektâşî Mûsikisi", TDV İslâm Ansiklopedisi (İstanbul: TDV Yayınları, 1992), 5/371-372.

[26] Akkuş - Aksoy Sugiyama, "Popülerleşen Alevi Deyişlerinde Anlamı Yakalama ve Doğasına Dokunma Tartışmaları", 87-97.

[27] Luca Casini vd., "Data-Driven Analysis of Text-Conditioned AI-Generated Music", arXiv preprint 2509.11824 (2025).

(i) yeni nesillerin geleneksel repertuvara karşı ilgi geliştirmesini kolaylaştırmakta, (ii) repertuvarın küresel müzik platformlarında "keşfedilebilir" hâle gelmesine yardımcı olmakta ve (iii) geleneksel icracıların dijital araçlarla yaratıcılıklarını zenginleştirebileceği yeni bir alan açmaktadır.

2.8.3. Etik İlkeler ve Bağlamın Korunması

Üretici yapay zekânın geleneksel müziklere uygulanması; veri sömürgeciliği, bağlam kaybı ve telif gibi ciddi etik meseleleri beraberinde getirmektedir. İrlanda halk müziği üzerinde yapılan çalışmalar, kültürel anlamın yapısal olarak nasıl yıprandığını göstermiştir.[28]

Bu çerçevede beş etik ilkenin esas alınması önerilir: (i) rıza ve katılım: dede, baba ve zâkirler süreçlere dahil edilmelidir; (ii) bağlamla birlikte kayıt: güfte ve ezginin yanı sıra ritüel bağlamı da kaydedilmelidir; (iii) şeffaflık: sınıflandırma kararları açıklanabilir olmalıdır; (iv) ticarî sınırlama: kutsal repertuvar yalnızca tıklanma ekonomisine indirgenmemelidir; (v) eğitsel çoğaltma: AI, meşk ilişkisini destekleyen bir araç olarak konumlandırılmalıdır.

3. SONUÇ

Bu bildiri, Alevi-Bektaşi geleneğine ait nefes ve deyiş formlarını Türk din musikisi merkezli bir perspektiften ve çok katmanlı bir analiz çerçevesi içinde ele almıştır. Çalışmada elde edilen başlıca sonuçlar şu şekilde özetlenebilir: (i) Nefes ve deyişler, ritüel işlev, meşruiyet, makam-usûl yapısı ve icra tavrı ölçütleri bakımından Türk din musikisinin müstakil ve kurucu formları arasında değerlendirilmelidir. (ii) Yirmi yedi farklı makamı kapsayan repertuvar; klasik Türk müziği, halk musikisi ve âşık geleneği arasında özgün bir köprü oluşturmaktadır. (iii) Bektaşi Devr-i Revânı ve Bektaşi Raksanı gibi geleneğe özgü usûller, repertuvarın özgün ritmik dilini kurmaktadır. (iv) "Zâhid Bizi Tan Eyleme", "Haydar Haydar", "Bu Yıl Bu Dağların Karı Erimez" ve "Şâh-ı Merdânın Avazı" gibi popüler örnekler, repertuvarın hem tasavvufî derinliğini hem toplumsal bellek işlevini somutlaştırmaktadır. (v) Yapay zekâ teknolojileri, doğru etik çerçeve içinde kullanıldığında bu repertuvarın belgelenmesi ve aktarımına katkı sunabilir; klasik icraların yeni düzenlemelerle yeniden üretilmesi geleneğe yönelik kamusal ilgiyi olumlu yönde besleyebilir.

Sonuç itibarıyla nefes ve deyişler; Türk din musikisinin kenarında değil, merkezinde yer alan, hem geleneksel meşk yoluyla hem de dijital imkânlarla geleceğe taşınması gereken canlı bir mirastır.

[28] Bob L. T. Sturm vd., "Innovation, Data Colonialism and Ethics: Critical Reflections on the Impacts of AI on Irish Traditional Music", Journal of New Music Research 53/4 (2024), 1-22.

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AKRAN DESTEĞİ YOLUYLA ÜNİVERSİTE ÖĞRENCİLERİNİN GÜÇLENDİRİLMESİ: TOPLULUK TEMELLİ ARAŞTIRMA VE EYLEM YAKLAŞIMI
EMPOWERING UNIVERSITY STUDENTS THROUGH PEER SUPPORT: A COMMUNITY-LED RESEARCH AND ACTION APPROACH

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ÖZET

Üniversiteye yeni adım atan öğrenciler için bu dönem çoğu zaman stres, kaygı ve yalnızlıkla iç içe geçer. Akran desteği ise tam da burada devreye giren, bu yükü hafifleten bir tampon görevi görür. Biz bu çalışmada, öğrencilerin akran desteğinden yoksun kalma deneyimlerini yakından inceledik; dahası, çözümü onlarla birlikte, kendi bağlamlarına oturan müdahaleler tasarlayarak aradık. Öğrenciyi yalnızca üzerinde araştırma yapılan bir özne sayan klasik nicel kalıpları geride bırakıp Topluluk Temelli Araştırma ve Eylem (TTAE) yaklaşımını benimsedik. İkinci sınıftan iki öğrenci, sürecin baştan sona içinde yer alan yardımcı araştırmacılar oldu. Akran desteği eksikliği çeken beş öğrenciyle, her biri bir öncekinin analizine göre şekillenen toplam yirmi beş yarı yapılandırılmış görüşme yaptık; ardından sıra eylem etkinliklerine geldi. Tematik çözümleme beş tema ortaya çıkardı: yalnız kalabalık, düşmek yasak, kurumsal boşluk, sessiz çığlık ve çözüm bende değil, bizde. Ortaya çıkan tablo şuydu: Akran desteği eksikliği, öğrencinin kişisel bir kusuru değil; rekabetçi akademik iklimin, sosyal damgalamanın ve kurumsal boşlukların beslediği yapısal bir sorun. Öğrencilerin kendi tasarladığı düşük eşikli sohbetler ve rekreatif spor etkinlikleri, sözcüklere dökülemeyen ama sahici bir bağ kurmayı kolaylaştırdı. Kısacası öğrenci ruh sağlığını korumak ve iyi oluşu güçlendirmek istiyorsak, öğrencinin sesini ve liderliğini kıyıda değil merkezde tutmak zorundayız.

Anahtar Kelimeler: Akran desteği, üniversite öğrencileri, topluluk temelli araştırma, öğrenci iyi oluşu, öğrenci ruh sağlığı.

ABSTRACT

This study investigates university students' experiences of peer support deficiency and, working alongside them, co-develops interventions attuned to their specific context. The transition into higher education tends to elevate stress, anxiety and loneliness; against these pressures, peer support functions as a critical protective buffer. Departing from the conventional quantitative paradigms that cast students as passive subjects, the research adopts a Community-Led Research and Action (CLRA) methodology. Two second-year students served as co-researchers, conducting twenty-five iterative, semi-structured interviews with five peers who had experienced a shortfall of support, followed by a series of collaboratively designed action events. Thematic analysis yielded five core themes: "The Lonely Crowd" (physical proximity coupled with emotional disconnection), "Falling is Forbidden" (the stigmatisation of help-seeking), "Institutional Emptiness" (distrust of formal mechanisms), "Silent Scream" (the emotional and somatic toll), and "The Solution is Not in Me, But in Us" (the action-oriented findings). Taken together, these themes reframe peer support deficiency as a systemic condition—one rooted in competitive academic cultures, social stigma and institutional gaps—rather than a matter of individual deficiency. The interventions students devised were deliberately modest: informal conversation and recreational sport. Yet they proved remarkably effective, opening up an authentic and frequently wordless mode of connection. The study's central claim follows directly: if the student mental health crisis is to be addressed in earnest, student voice and leadership must be relocated from the margins to the centre of institutional response.

Keywords: Peer support, university students, community-led research, student well-being, student mental health.

1. INTRODUCTION

The transition to university life constitutes a period of marked personal growth, intellectual development and social exploration. It is, at the same time, an interval frequently shadowed by heightened stress, anxiety and loneliness (Campbell et al., 2022; Matsuo et al., 2022). The pressures students confront are varied and cumulative—escalating academic demands, financial precarity, social expectation, and, for many, separation from the support networks on which they had long depended. Among the most robust protective factors against these strains is peer support: the assistance, encouragement and mutual understanding that students extend to one another, whether informally or through structured provision (Suresh et al., 2021; Richard et al., 2022).

Variously designated peer learning, peer mentoring or peer-assisted learning, the phenomenon rests on a single premise—students aiding students, academically, socially and emotionally, across a spectrum of collaborative activity (Topping, 2005; Gamlath, 2022). The supporting evidence is considerable. Peer support programmes have been shown to enhance mental health and well-being, attenuate stress and anxiety, strengthen self-confidence and cultivate a sense of community (Oduwaye et al., 2024; Crisp et al., 2020; Worley et al., 2023).

Its benefits extend well beyond the affective domain. Participation has been associated with stronger academic performance (Altermatt, 2016; Huang, 2023), with higher rates of retention and degree completion (van der Meer et al., 2017), and with deeper engagement in university life (Hakimzadeh et al., 2016). It also eases the passage into higher education. That mattered most, the literature suggests, for first-year and international students—those who must negotiate the further barriers of language, culture and an unfamiliar academic system (Lee, 2017; Martirosyan et al., 2019).

These outcomes rest on a coherent theoretical foundation, for peer support answers to needs of considerable depth. Self-determination theory maintains that three constituents—competence, autonomy and relatedness—are indispensable to well-being and to intrinsically grounded motivation. Peer support nourishes two of them directly: relatedness, through the felt sense of connection to others, and competence, as students learn with and from their peers in settings unencumbered by hierarchy. Social support theory advances a congruent argument, construing the emotional, instrumental and informational provision exchanged among peers as a buffer against stress.

And yet, notwithstanding this widely acknowledged value, a substantial proportion of students report a pronounced sense of its absence. They describe being encircled by peers while remaining profoundly isolated; they articulate a desire for connection even as they encounter the recurrent barriers of stigma, competition and institutional inadequacy. This disjuncture—between the ascribed importance of peer support and its lived scarcity—constitutes a pressing concern for higher education institutions across the globe.

Scholarship on peer support has been predominantly quantitative, oriented toward measurable outcomes such as grade point averages, retention rates and mental health indices (John et al., 2018; Pointon-Haas et al., 2023). Valuable as such work undoubtedly is, it tends to leave untouched the nuanced, embodied and context-dependent registers through which students actually undergo peer support deficiency. A more fundamental limitation attends these paradigms: they position students as objects of investigation rather than as agents in apprehending and redressing their own needs.

The present study responds to these constraints by adopting a Community-Led Research and Action (CLRA) methodology. CLRA is an emergent approach in which community members—here, the students themselves—direct every phase of inquiry and action, from the framing of the problem through data collection, analysis and the design of interventions (van Stapele et al., 2018; Woensdregt et al., 2023). By installing two students as co-researchers and engaging five peer participants in iterative cycles of inquiry and action, the study seeks to generate situated, richly contextualised knowledge of peer support deficiency while concurrently catalysing meaningful change.

Three questions guide the inquiry. First, how do university students experience peer support deficiency in the everyday texture of their academic and social lives? Second, what contextual, emotional and practical dimensions give these experiences their particular shape? And third, what forms

of community-led action might redress this deficiency in ways that prove both sustainable and culturally resonant?

2. RESEARCH AND FINDINGS

2.1. Method

The study was structured around Community-Led Research and Action (CLRA) as its methodological framework. CLRA is a participatory approach that vests leadership in community members themselves—those whose lives are directly implicated in the issue under study—across the full arc of research and action (CREATE, 2020). It diverges from conventional participatory action research (PAR) on a decisive point: whereas PAR frequently retains academic researchers as principal decision-makers, CLRA locates ownership, control and leadership unambiguously within the community.

Several principles underpin the approach. Community members, rather than external authorities, set the research agenda; the expertise that community researchers already possess is both recognised and actively mobilised. Animating the whole undertaking is a distinct constellation of values—empowerment, supportive relationship, social transformation, respect for diversity. Findings are meant to remain intelligible and pertinent to the wider community, not sequestered within academic circuits. And not least, the process looks beyond itself: it aims at durable action, change that outlasts the project's own lifespan (Woensdregt et al., 2023; van Stapele et al., 2018).

Such an orientation renders CLRA especially well suited to sensitive or intricate subjects—the very terrain on which established methods tend to elicit socially desirable responses. Operating as insiders, community researchers reach what an external investigator would likely miss: tacit knowledge, quotidian practice, the unspoken dynamics that structure a community (CREATE, 2020). The present case bore this out. Far from external observers, the two student researchers belonged to the university community and had themselves endured peer support deficiency—a circumstance that lent them both experiential expertise and a legitimacy participants readily recognised.

2.1.1. Research Setting and Participants

The research was conducted at a university whose students had previously voiced concern over inadequate peer support. Two of them—one female, one male, both in their second year of study—assumed the roles of co-researcher and co-author. They proceeded to recruit five participants (three female, two male) drawn from a range of faculties and spanning the first through fourth years. Eligibility rested on three criteria: a self-identified experience of peer support deficiency, a willingness to undertake five in-depth interviews, and availability to attend the subsequent action events.

2.1.2. Data Collection

Each participant took part in five semi-structured, in-depth interviews, twenty-five in all. Lasting between sixty and ninety minutes, these were held in private, comfortable spaces across the campus. No fixed schedule governed them. Rather, the guide evolved iteratively, each successive encounter informed by a preliminary analysis of the one before—an arrangement consonant with the cyclical logic of CLRA (CREATE, 2020).

Experience anchored the first three interviews: the specific contexts in which peer support deficiency surfaced, the emotional responses it provoked, the causes participants attributed to it. A shift of register marked the fourth, which invited participants to envision and then design interventions they would find genuinely meaningful. Conducted in the aftermath of the action events, the fifth gave them room to reflect on what, if anything, had changed.

2.2. Results

Content analysis distilled five core themes that together characterise the experience of peer support deficiency. They were designated as follows: the Lonely Crowd, Falling Forbidden, the Institutional Gap, the Silent Scream, and The Solution Is Not Me, It's Us.

The first theme, the Lonely Crowd, denotes physical togetherness shadowed by emotional detachment. With striking consistency, participants returned to a profound loneliness endured in the very midst of their peers; campus, in their accounts, was at once crowded and disconnected. As one participant explained:

"We sit side-by-side in class, we share notes, but nobody really asks how I feel. It's like we're all experiencing the same loneliness."

The competitive academic milieu emerged as a salient obstacle. Where "everyone sees each other as rivals," the pursuit of authentic connection comes to feel like an exposure few are willing to risk.

The second theme, Falling Forbidden, captures young people's apprehension of stigma when seeking support. A powerful cultural norm pervaded participants' accounts—the conviction that to require support is to betray weakness—and it bore down most heavily upon first-year and male participants. One recounted the following:

"I asked a friend, 'I'm struggling in class, can we study together?' She laughed and said, 'Still haven't gotten used to it?' I never asked anyone again."

What proved especially telling was the bidirectionality of the stigma: participants hesitated no less to extend support than to seek it, wary of appearing either condescending or intrusive.

A third theme, the institutional gap, concerns the erosion of trust in formal support mechanisms. Whatever provisions the university did offer—counselling, peer mentoring programmes—were variously unknown, inaccessible, or judged unreliable. Compounding this, participants feared that soliciting formal assistance might compromise their academic standing or leave a lasting mark on their record. As one put it:

"If I go to counseling, will my professor hear about it? Will it affect my grade? I can't risk that. But a friend… a friend just listens."

Even the peer networks that arose organically were portrayed as fragmentary and contingent upon chance: "It all depends on what class you end up in."

The fourth theme, the silent scream, drew the body into a domain too often confined to the mind. The privation of peer support registered not only socially but somatically. Participants reported insomnia, chronic fatigue, a draining away of motivation and a pervasive sense of emptiness. Digital communication, far from mitigating the condition, was experienced as aggravating it:

"Sometimes I want to share something, but with whom? I communicate with hundreds of people, but no one really asks 'how are you?' It's like I'm inside a glass bubble and everyone is just passing me by."

One participant distilled the matter in a phrase that lingered: "An emoji doesn't comfort you."

The final theme inverted the very framing of the problem: the solution resides not in me but in us. Here participants insisted upon the necessity of genuine relationship—the conviction that whatever had been ruptured could be repaired only in common, never in isolation.

2.3. Discussion

Employing a Community-Led Research and Action methodology, this study has examined university students' experiences of peer support deficiency and, in concert with them, developed contextually attuned interventions. Its findings bear upon theory, practice and method alike.

Beyond any deficit of individual social skill or temperamental introversion, the five core themes establish something larger at work. Peer support deficiency is produced—and continually reproduced—through a confluence of forces: an academic culture that penalises vulnerability; a stigma adhering to help-seeking in both its giving and its receiving; support mechanisms that students distrust or cannot

reach; and a digital milieu that trades substantive connection for superficial exchange. Read in this way, the familiar individualised remedies—the social-skills workshop chief among them—miss their mark. What the evidence demands instead is change at the level of culture and structure.

In accord with prior scholarship (Campbell et al., 2022; Diehl et al., 2018), participants described loneliness amid physical presence—a finding that complicates any simplistic metric of social integration. The notion of "being alone together" carries pointed implications for the design of campus environments: to furnish spaces for interaction avails little if the norms governing those spaces remain competitive and judgemental.

The action phase yielded a heartening demonstration. Comparatively simple and low-cost events—unstructured conversation, the shared airing of difficulties, recreational sport—sufficed to effect meaningful shifts in participants' sense of connection. Their efficacy owed nothing to professional facilitation or to evidence-based design in any narrow sense; it derived, rather, from the fact that students had conceived them, for students, in a manner that lowered the threshold to authentic interaction.

One outcome warrants particular emphasis. Sport afforded modes of support that conversation simply could not reach. For participants who struggle to put their needs into words, or who find the conventional "support group" forbidding, such embodied, non-verbal connection may prove uniquely valuable. The corollary is concrete: future programmes would do well to weave physical, recreational and creative activity into the conversational formats that now predominate. As a method, CLRA earned its place here, surfacing nuanced, context-bound knowledge and generating low-threshold, sustainable interventions. Institutions across the world now contend with deepening crises of student mental health. If those crises are to be met, the voices and leadership of students must migrate from the margins to the centre. Peer support is neither a luxury nor an adjunct. It is a fundamental condition of academic and human flourishing.

3. CONCLUSION

This study has demonstrated that peer support deficiency among university students is not, in the final analysis, an individual failing but a systemic one—shaped by academic competition, by stigma, by an attenuated trust in institutions, and by the superficiality of digital interaction. The Community-Led Research and Action approach enabled students to render these experiences in their own terms and to design low-threshold practices capable of forging meaningful connection. The implication for universities is clear: they would be well advised to move beyond top-down and strictly formal mechanisms, and to cultivate peer support structures that are participatory, student-led and culturally responsive. Conceived in these terms, peer support is no ancillary service but a foundational condition of academic engagement, of belonging, and of human flourishing.

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SOLAR PELTIER COOLING SYSTEMS FOR SUSTAINABLE ATMOSPHERIC WATER HARVESTING: A COMPREHENSIVE REVIEW

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1.ABSTRACT

Freshwater scarcity remains a critical issue in many coastal and humid regions despite the abundance of atmospheric moisture. This review focuses on the development and experimental evaluation of a Thermoelectric Fresh Water Generator (TFWG) that utilizes the thermoelectric cooling effect to condense water vapor from ambient air. The system integrates a solar panel connected to a battery, which powers a Peltier module along with a heat sink and cooling fan assembly. The cold side of the Peltier module is attached to an aluminium rod to enhance heat transfer and promote condensation, while the heat sink dissipates the generated heat from the hot side. When electric current flows through the module, a temperature gradient is established, leading to surface cooling and subsequent condensation of atmospheric moisture into liquid water. The setup operates efficiently in environments with relative humidity above 60 percent and offers a sustainable, renewable approach to freshwater generation. This paper reviews the underlying thermoelectric principles, experimental design, and performance optimization strategies to enhance condensation rate and energy efficiency for practical deployment in water-scarce humid areas.

Keywords:

Thermoelectric cooling; dehumidification; fresh water production; Peltier.

2. INTRODUCTION

Freshwater scarcity has become a critical global challenge, driven by rapid population growth, climate variability, and increasing demand for potable water. Many regions with high atmospheric humidity still face drinking-water shortages due to inadequate infrastructure and unreliable water distribution systems. As a result, atmospheric water harvesting (AWH) has emerged as a promising technology capable of extracting moisture directly from air and providing decentralized, small-scale freshwater generation for remote or water-stressed areas (Nikkhah et al., 2023).Among various AWH approaches, condensation-based systems powered by thermoelectric coolers (TECs) have gained significant attention. TECs operate using the Peltier effect, enabling compact, refrigerant-free, and environmentally friendly cooling suitable for portable atmospheric water generators. However, their performance is strongly influenced by environmental conditions, heat-exchanger design, and the ability to maintain an adequate temperature difference across the TEC module (Eslami et al., 2018).

To improve the sustainability and energy efficiency of TEC-based AWH systems, researchers have explored integrating solar photovoltaic (PV) power. Solar-driven TEC devices reduce operating costs, support off-grid functionality, and enable deployment in coastal, tropical, or rural regions with abundant sunlight. Recent advancements demonstrate that solar-assisted TEC systems, when combined with optimized heat exchangers and airflow management, can significantly enhance water yield while lowering energy consumption

3.ATMOSPHERIC WATER HARVESTING (AWH) TECHNOLOGIES

Atmospheric Water Harvesting (AWH) encompasses a range of techniques designed to extract water vapor from humid air and convert it into liquid water. These technologies are increasingly studied as reliable, decentralized solutions for regions with limited access to surface or groundwater sources. AWH methods typically fall under three categories: condensation-based systems, sorption-based systems, and hybrid configurations. Condensation remains the most widely adopted approach due to its direct conversion of atmospheric moisture into potable water when cooled below the dew point (Cendoya et al., 2023).Sorption-based AWH systems use hygroscopic materials—such as desiccants or metal–organic frameworks—to capture water vapor and later release it through controlled heating. These technologies are advantageous in areas with low relative humidity but generally require additional thermal input during regeneration. Recent reviews highlight how material selection, adsorption capacity, and regeneration efficiency significantly influence system performance and suitability for specific climate zones.

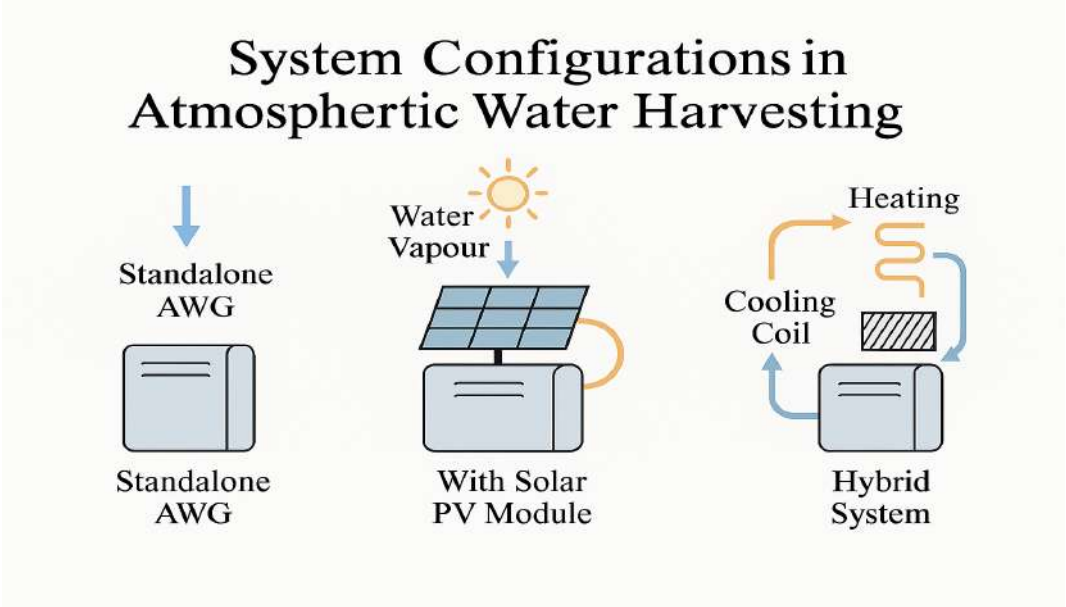


Fig1.Schematic illustration of atmospheric water harvesting processes, including condensation, sorption, and hybrid mechanisms

Hybrid AWH systems combine passive and active techniques to improve overall water yield and operational efficiency. Examples include coupling desiccant absorption with thermoelectric cooling or integrating radiative cooling surfaces with TEC modules. Such systems enhance moisture capture under fluctuating environmental conditions while reducing the cooling load required for dew-point condensation. Numerical and thermal analyses further show that optimizing airflow, heat exchanger geometry, and condensation surface temperature leads to substantial gains in water productivity (Eslami et al., 2018).

Table 1 — Comparison of Major Atmospheric Water Harvesting (AWH) Technologies

AWH Technology	Working Principle	Advantages	Limitations	Best Climate
Condensation (Thermoelectric/Peltier)	Air is cooled below dew point to form liquid water	Compact, no refrigerants, simple operation	High energy demand, depends on humidity	Humid & coastal regions
Sorption (Desiccant-based)	Hygroscopic materials absorb moisture and release when heated	Works in low humidity, scalable	Requires heating for regeneration	Semi-arid to moderate RH areas
Hybrid (Condensation + Sorption / Radiative Cooling)	Combines moisture absorption with active cooling	Higher yield, more efficient, stable output	Complex design, higher cost	Wide climate range

4.THERMOELECTRIC (PELTIER) COOLING FOR AWH

Thermoelectric cooling operates on the Peltier effect, where an applied electrical current transfers heat from one side of a semiconductor module to the other, creating a cold surface suitable for moisture condensation. This solid-state cooling mechanism makes thermoelectric coolers (TECs) attractive for atmospheric water harvesting due to their compact size, absence of chemical refrigerants, low maintenance requirements, and ability to function reliably under varying environmental conditions. Studies emphasize that TECs can achieve dew-point temperatures effectively when integrated with well-designed heat exchangers and adequate airflow systems (John et al., 2022).

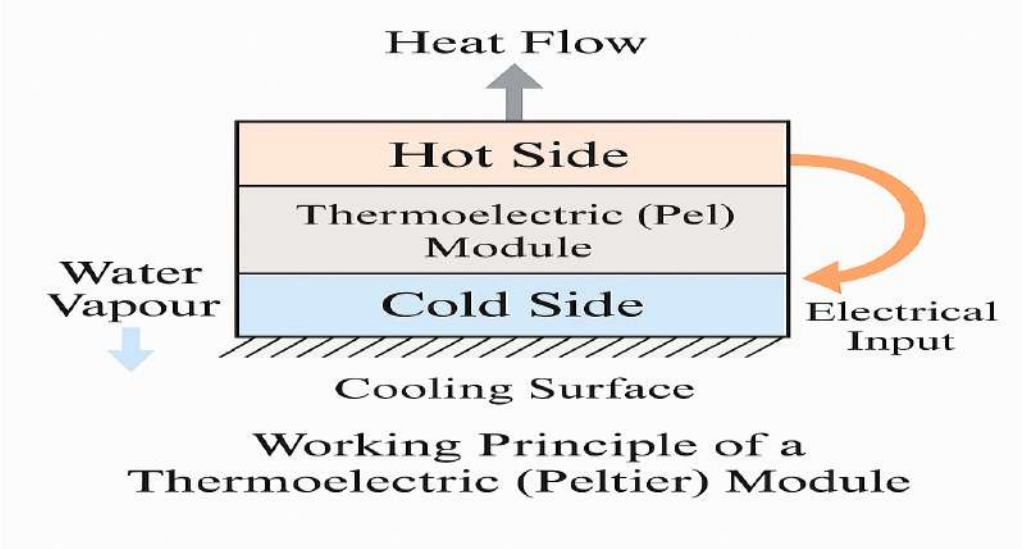


Fig 2. Working principle of a thermoelectric (Peltier) module showing heat absorption from the cold side and heat rejection from the hot side.

However, thermoelectric cooling efficiency is inherently limited by the low Coefficient of Performance (COP) of TEC modules. This makes effective heat removal from the hot side a critical design factor, as insufficient dissipation of thermal energy reduces the temperature gradient required for condensation. Numerical and experimental investigations reveal that optimizing heat sink configuration, enhancing fin geometry, and applying water-cooled heat exchangers can significantly improve TEC performance in AWH systems (Eslami et al., 2018). Recent studies also highlight the growing use of advanced modeling and artificial intelligence to optimize TEC operation under fluctuating climatic conditions. Machine-learning-based frameworks and deep neural network models have been used to predict condensation rates, optimize TEC input current, and adjust operating conditions in real time to improve performance. These intelligent control strategies help maintain stable dew-point cooling, increase water yield, and reduce energy consumption by dynamically matching the TEC's operating profile with environmental variations (Ashour et al., 2025).

5.SOLAR-POWERED PELTIER-BASED AWH SYSTEMS

Solar-powered thermoelectric atmospheric water harvesting (AWH) systems utilize photovoltaic (PV) panels to supply the electrical power required for cooling the Peltier modules. This integration significantly enhances sustainability by reducing reliance on grid electricity and allowing decentralized, off-grid water production—especially in rural and coastal regions with high solar irradiance. Solar-driven TEC systems have demonstrated improved energy efficiency and reduced operating cost when compared to electrically powered alternatives, making them promising candidates for long-term freshwater generation in remote environments (Sanaye et al., 2023).

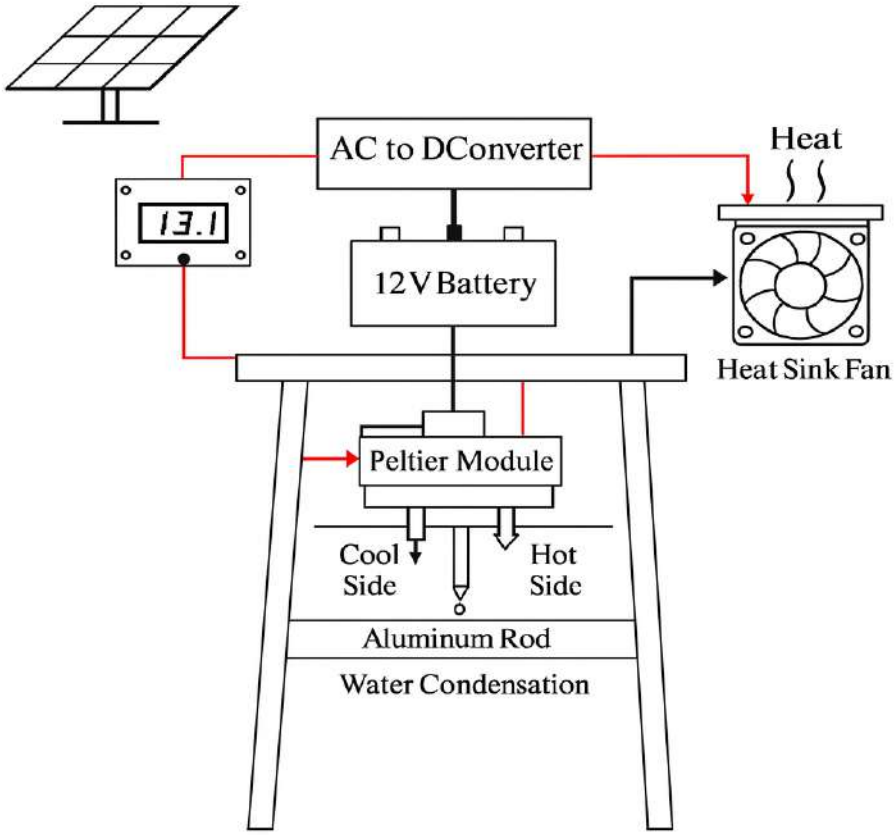


Fig 3. Solar-powered thermoelectric atmospheric water harvesting system illustrating electrical configuration, thermal management, and condensation process.

The performance of solar-TEC AWH systems strongly depends on the design and matching of components such as PV panel size, power regulation systems, and battery storage. Efficient power matching ensures that the TEC modules operate within their optimal current range to maintain a sufficient temperature difference for condensation. Studies show that incorporating cooling-recovery heat exchangers, improved airflow management, and well-insulated condensation surfaces can significantly increase water yield while utilizing solar energy more effectively. These enhancements help maintain system stability even under fluctuating sunlight conditions.

Recent advancements also include hybrid solar configurations that combine PV electricity with radiative cooling or sorption-assisted moisture capture to reduce the cooling load on Peltier modules. Such hybrid systems can extend operational hours into low-sunlight periods and improve water productivity in climates with variable humidity. Numerical and experimental studies indicate that solar-assisted TEC systems, when paired with optimized thermal design, offer a highly sustainable approach to atmospheric water generation, providing an adaptable solution to global freshwater scarcity challenges (Cendoya et al., 2023).

6.COMPARATIVE REVIEW

The four selected studies collectively provide strong experimental, numerical, and techno-economic foundations for understanding the performance of thermoelectric-based atmospheric water harvesting systems. The first study demonstrates the importance of geometric and thermal optimization by

developing an innovative TEC-based system supported by computational fluid dynamics (CFD). The results showed a strong correlation between simulation and experimental data, with less than 6% deviation—highlighting the reliability of numerical models for predicting AWH performance (Sanaye et al., 2023).

The second study expands the field by evaluating hybrid or solar-assisted configurations, emphasizing the importance of energy recovery mechanisms and improved condensation surfaces. For example, systems that recover thermal energy from the TEC hot side and reintroduce it into the cooling pathway demonstrate noticeable increases in water production, especially under humid environmental conditions. Such systems indicate the potential for solar-thermoelectric designs to deliver higher energy efficiency while maintaining stable freshwater output in real climates

A third key contribution comes from the thermo-economic evaluation of TEC configurations. This work systematically analyzed more than 300 system variations and identified the counter-flow heat exchanger as the most efficient and cost-effective design. The results show that thermoelectric atmospheric water generators can achieve competitive cost per liter when heat exchanger performance is optimized, demonstrating the importance of coupling thermal design with cost modeling (Moosavi Shoar & Kouhikamali, 2024).

In parallel, comprehensive reviews of AWH technologies emphasize that TEC systems perform best in medium-to-high humidity conditions, whereas sorption-based systems excel in low-humidity environments. These broader reviews position thermoelectric AWH as one component within a larger technological ecosystem, reinforcing its suitability for humid and coastal regions while highlighting opportunities for hybridization with desiccants and radiative cooling strategies.

7.KEY PERFORMANCE PARAMETERS.

Evaluating the performance of thermoelectric atmospheric water harvesting (AWH) systems requires analyzing several critical parameters that influence overall efficiency and water productivity. One of the most important metrics is water yield, typically measured in mL/h or L/day. Water yield depends on ambient humidity, dew-point depression, airflow rate, and TEC temperature difference. Experimental systems have shown that optimized condensation surfaces and airflow improvements can significantly increase hourly water production, especially under humid climatic conditions (Sanaye et al., 2023.)

Another essential parameter is Specific Energy Consumption (SEC), expressed in kWh per liter of water produced. Thermoelectric systems generally have higher SEC than traditional refrigeration systems due to their low Coefficient of Performance (COP). However, studies demonstrate that proper heat exchanger design, counter-flow arrangements, and optimized TEC current inputs can substantially reduce energy demand. Thermo-economic evaluations show that systems with efficient heat exchange configurations achieve more favorable SEC values, improving the feasibility of TEC-based water production (Moosavi Shoar & Kouhikamali, 2024).

Table 2 — Key Performance Parameters Affecting TEC-Based AWH Systems

Performance Parameter	Description	Typical Value/Range	Importance
Water Yield (mL/h or L/day)	Amount of water collected within a time period	150–500 mL per TEC module	Primary measure of system productivity

Performance Parameter	Description	Typical Value/Range	Importance
Specific Energy Consumption (kWh/L)	Energy required to produce one liter of water	0.5–1.8 kWh/L	Determines system energy efficiency & cost
Coefficient of Performance (COP)	Cooling efficiency ratio of TEC	0.3–0.6	Higher COP → better cooling and water yield
ΔT (Temperature Difference)	Difference between cold & hot sides of TEC	15–25°C	Controls condensation ability below dew point
Heat Exchanger Effectiveness (ηHX)	Efficiency of heat removal on hot side	Medium to high	Critical for maintaining TEC temperature gradient

The Coefficient of Performance (COP), temperature difference (ΔT) across the TEC module, and heat exchanger effectiveness also play major roles in determining system performance. A larger ΔT improves dew-point cooling but increases power consumption, requiring a balance between cooling capacity and efficiency. Advanced numerical and thermal analyses highlight that improving heat exchanger effectiveness enhances TEC stability and increases water yield. When solar energy is integrated into the system, additional metrics—such as solar-to-water efficiency and PV matching efficiency—become relevant, providing a clearer picture of system energy sustainability.

8.CHALLENGES & LIMITATIONS

Despite their growing potential, thermoelectric (TEC)-based atmospheric water harvesting (AWH) systems face several technical limitations that hinder large-scale adoption. One of the primary challenges is the inherently low Coefficient of Performance (COP) of Peltier modules. TECs typically consume considerable electrical power to maintain the required temperature difference for condensation, which increases operational costs and reduces overall system efficiency. Studies indicate that poor heat removal from the hot side of the TEC is one of the main reasons for reduced ΔT and lower water yield, demonstrating the importance of optimized thermal management

Environmental dependency presents another significant limitation. TEC-based AWH performs best in regions with high relative humidity; however, performance drops sharply under low-humidity conditions. This restricts deployment in arid climates unless supplemented with hybrid technologies such as desiccant-based pre-humidification or radiative cooling surfaces. Comprehensive reviews show that while sorption systems handle low-humidity environments effectively, TEC-based systems are mainly suitable for coastal or tropical regions where dew-point cooling can be achieved more easily (Nikkhah et al., 2023).

Economic and design challenges also affect system viability. Thermoeconomic analyses reveal that TEC systems require carefully engineered heat exchangers, insulation, and power management systems to maintain an acceptable cost per liter of water. Complex designs—such as counter-flow heat exchangers or multi-stage TEC configurations—improve performance but increase material and fabrication costs. Even in solar-powered setups, fluctuations in sunlight and the need for energy storage raise initial investment. These factors highlight the necessity of balancing performance improvements with economic practicality to achieve real-world implementation.

9.FUTURE SCOPE

Future development of thermoelectric (TEC)-based atmospheric water harvesting (AWH) systems will focus heavily on improving the efficiency of thermoelectric materials and heat exchangers. Increasing the thermoelectric figure of merit (ZT) is essential for reducing energy consumption and improving cooling performance. Research suggests that advanced semiconductor materials, optimized fin geometries, and microchannel heat exchangers can significantly enhance heat removal, supporting larger temperature gradients and higher water yields in upcoming systems.

Another major direction involves the integration of hybrid energy and cooling technologies. Combining TEC modules with radiative sky cooling, desiccant-based moisture capture, or solar-thermal collectors can reduce the electrical load on Peltier modules and expand system functionality across diverse climate conditions. Studies on atmospheric water harvesting technologies highlight the potential of these hybrid configurations to improve performance in both high-humidity and low-humidity environments, widening the applicability of TEC-based systems beyond coastal regions (Nikkhah et al., 2023).

Artificial intelligence and predictive control strategies will also play a crucial role in the next generation of AWH systems. Deep learning models and optimization algorithms can dynamically adjust TEC current, manage airflow, and estimate condensation potential under real-time climatic variations. These smart controllers enhance system adaptability, minimize energy waste, and maximize daily water output. Recent advancements show that machine-learning-driven optimization can significantly improve operational performance, making TEC-based AWH systems more robust and scalable for real-world deployment (Ashour et al., 2025).

10.CONCLUSION

Thermoelectric-based atmospheric water harvesting (AWH) systems have gained significant attention as a sustainable and decentralized solution for freshwater generation. Their ability to condense moisture directly from humid air, combined with solid-state operation and the absence of chemical refrigerants, makes them especially suitable for remote, off-grid, or coastal regions. However, achieving high cooling performance depends strongly on effective heat dissipation, optimized airflow pathways, and adequate temperature gradients across the TEC surfaces, which remain areas requiring continued improvement (Eslami et al., 2018).

The integration of solar energy has further strengthened the viability of TEC-based AWH systems by reducing dependency on grid electricity and lowering operating costs. Solar-assisted designs—particularly those using advanced heat exchangers or hybrid components—have demonstrated improved energy efficiency and greater water yield in experimental studies. These advancements underscore the importance of combining renewable energy sources with optimized thermal management strategies to create more economically and environmentally sustainable AWH solutions.

Although promising, thermoelectric AWH systems still face challenges related to low Coefficient of Performance (COP), high energy consumption, and climate sensitivity. Future progress depends on the development of high-ZT TEC materials, intelligent control systems, and hybrid cooling technologies that enhance performance under dynamic environmental conditions. With continued advancements in system design, machine learning optimization, and renewable integration, TEC-based AWH systems have strong potential to become practical, scalable solutions for addressing global freshwater scarcity (Ashour et al., 2025).

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DETERMINATION OF THE EFFECT OF ONTOGENETIC VARIABILITY ON DUALEX VALUES IN SAGE (*Salvia officinalis* L.)

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Abstract

Medicinal and aromatic plants are cultivated due to the bioactive compounds they contain. These bioactive compounds show significant variations depending on the plant organ, developmental stage, and harvest time. Therefore, it is crucial to have a thorough understanding of the changes in bioactive compounds in medicinal and aromatic plants and to harvest them at the stage when the active constituents are at their highest levels. Sage (***Salvia officinalis*** L.) is a valuable medicinal and aromatic plant belonging to the Lamiaceae family. Species of the genus ***Salvia*** are generally rich in essential oils and are therefore of great importance in pharmacology and the perfume industry. The genus ***Salvia***, which belongs to the Lamiaceae (Labiatae) family, comprises approximately 900 taxa worldwide, predominantly distributed across the Americas and Southwest Asia.

In order to determine the effect of ontogenetic variability on biochemical parameters in sage plants, plant samples cultivated in the Medicinal and Aromatic Plants Garden of the Faculty of Agriculture at Van Yüzüncü Yıl University in 2024 were used as experimental material. Sampling was carried out at three different developmental stages: pre-flowering, full flowering, and post-flowering. Prior to harvest at each stage, chlorophyll content (µg/cm²), nitrogen balance index (NBI, mg/g), flavonol content, and anthocyanin content (dx) were measured on the leaves using a Dualex Scientific+ device (FORCE-A, France). Measurements were performed in real time and non-destructively using the leaf clip sensor of the instrument.

The results of the study indicated that different harvest dates did not cause statistically significant differences among the examined parameters. Nitrogen balance index values ranged between 10.62 and 11.08 mg/g, chlorophyll content varied from 21.04 to 21.41 µg/cm², flavonol content ranged between 1.95 and 2.01 (dx), and anthocyanin content varied between 0.086 and 0.10 (dx).

Keywords: Sage, Dualex values, *Salvia officinalis* L., Ontogenetic variability

Acknowledgement

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ADAÇAYINDA (*Salvia officinalis* L.) ONTOGENETİK VARYABİLİTENİN DUALEX DEĞERLERİ ÜZERİNDEKİ ETKİSİNİN BELİRLENMESİ

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Özet

Tıbbi ve aromatik bitkiler, içerdikleri biyoaktif maddeler nedeniyle kültürü yapılan bitkilerdir. Biyoaktif maddeler, bitkinin farklı organlarına, hayat devrelerine ve biçim zamanlarına göre önemli değişiklikler gösterir. Bu nedenle tıbbi ve aromatik bitkilerin biyoaktif madde değişiminin çok iyi bilmesi ve etken maddelerce en zengin olduğu dönemde hasat edilmesi oldukça önemlidir. Adaçayı (*Salvia officinalis* L.), Lamiaceae familyasından değerli bir tıbbi ve aromatik bitkidir. Salvia cinsinde yer alan türler genellikle uçucu yağ zengindirler ve bu nedenle farmokolojik olarak ve parfümeri sanayinde önemlidirler. Lamiaceae (Labiatae) familyasına bağlı olan Salvia cinsinin dünya genelinde yayılış gösteren 900 kadar taksonu bulunmakla birlikte bunlar çoğunlukla Amerika ve Güney-Batı Asya kıtalarında yayılış göstermektedir.

Adaçayı bitkisinde ontogenetik varyabilitenin, biyokimyasal parametreleri üzerine etkisini belirlemek amacıyla; 2024 yılında; Van Yüzüncü Yıl Üniversitesi Ziraat Fakültesi, Tıbbi ve Aromatik Bitkiler Bahçesi' nde yetiştirilen bitkilerden alınan örnekler materyal olarak kullanılmıştır. Denemede 3 farklı dönemde; çiçeklenme öncesi, tam çiçeklenme ve çiçeklenme sonrası dönem olmak üzere örnekleme yapılmıştır. Denemede, bu dönemler dikkate alınmak üzere hasat yapılmadan hemen öncesinde; yaprak üzerinde klorofil (µg/cm^2), azot balans indeksi (NBI-mg/g), flavonol ve antosiyanin içeriği (dx) sensörde bulunan yaprak klipsi sayesinde gerçek zamanlı ve tahribatsız olarak ölçüm yapabilen Dualex Scientific$^+$(FORCE-A, Fransa) cihazı ile ölçümler yapılmıştır. Araştırma sonucunda; istatistiksel olarak farklı hasat tarihlerinin, incelenen parametreler arasında önemli bir farklılığa neden olmadığı belirlenmiş ve azot balans indeksi 10.62-11.08 mg/g, klorofil içeriği 21.04-21.41 µg/cm^2, flavonol içeriği 1.95-2.01 (dx) ve antosiyanin içeriğinin 0.086-0.10 (dx) arasında değiştiği kaydedilmiştir.

Anahtar Kelimeler: Adaçayı, Dualex değerleri, *Salvia officinalis* L., Ontogenetik varyabilite

Teşekkür

Bu çalışmaya, FYL-2024-11556 no'lu proje kapsamında destek sağlayan Van Yüzüncü Yıl Üniversitesi Bilimsel Araştırma Projeleri Koordinasyon Birimi'ne teşekkür ederiz.

1.Introduction

Medicinal and aromatic plants are important plant groups cultivated due to the bioactive (active) compounds they contain. The amount and composition of these bioactive substances may vary significantly depending on plant organs, developmental stages (life cycles), and harvest time. Therefore, producers of medicinal and aromatic plants should have a good understanding of the variability of bioactive compounds in the species being cultivated and should carry out harvesting at the organ, developmental stage, and time when the plant is richest in active compounds (Başyiğit, 2017).

In medicinal and aromatic plants, essential oil content and essential oil components vary under the influence of environmental conditions, genetic structure, and cultivation practices (Hadiana, 2008). Similarly, in aromatic plants, essential oil quantity and composition may differ depending on the developmental stage at which harvesting is performed. Considering this, determining the correct harvest time is of great importance during the cultivation of aromatic plants in order to obtain maximum essential oil yield and to ensure products with an essential oil composition suitable for the production purpose. Numerous studies have shown that the optimal harvest time varies depending on plant species as well as the climatic and soil conditions of the production area (Aziz et al., 2013; Lakusic et al., 2013; Mammadov, 2014).

Among the medicinal and aromatic plants with high economic and therapeutic value in the flora of Türkiye, sage occupies an important place. The genus ***Salvia***, belonging to the Lamiaceae (syn. Labiatae) family, is represented by 89 species and 93 taxa according to the records of the Turkish Plants Data Service (TÜBİVES). Several ***Salvia*** species, including ***Salvia fruticosa*** Mill., known as "Anatolian sage," and ***S. tomentosa*** Mill., locally referred to as "şalba/çalba," as well as others such as ***S. cryptantha***, ***S. multicaulis***, ***S. aramisis***, and ***S. sclarea***, are collected from the wild, marketed, and economically utilized. ***S. sclarea*** L. is naturally distributed in almost all regions except Western Anatolia, ***S. tomentosa*** Mill. occurs in all regions except Eastern and Southeastern Anatolia, while ***S. fruticosa*** Mill. is naturally found in the Aegean, Marmara, and Western Mediterranean regions (Baydar, 2022).

The fact that approximately 58% of ***Salvia*** taxa in the flora of Türkiye are endemic makes this genus highly valuable in terms of biodiversity. However, due to uncontrolled and intensive harvesting from natural habitats, the future of many sage species is under threat. In this context, the domestication of sage species that have high economic value but are collected from the wild is of great importance. In Türkiye, the two main species cultivated for economic purposes are "common sage" (***Salvia officinalis*** L.) and "Anatolian sage" (***Salvia fruticosa*** Mill.). Although ***S. officinalis*** L. does not naturally occur in Türkiye, it can be successfully cultivated under agricultural conditions (Ceylan et al., 1989; Ceylan et al., 1990).

Turkey holds an important position in global medicinal and aromatic plant production and trade, with an annual export volume of approximately 70,000 tons (>225 million USD) and an import volume of 35,000 tons (>70 million USD) (Boztaş et al., 2025; Comtrade, 2025). In 2024, Türkiye's exports of spice, coffee, and tea products amounted to approximately 378 million USD, while imports reached about 660 million USD (TÜİK, 2025). The country is particularly among the leading global producers and exporters of bay laurel, thyme, and sage. In Türkiye, the cultivation area of Anatolian sage and common sage was determined to be approximately 15,000 decares in 2025.

Sage production is concentrated mainly in the Aegean Region, particularly in Denizli, Uşak, and Muğla; in the Mediterranean Region, especially Antalya and Burdur; in the Marmara Region, particularly Sakarya, Balıkesir, and Tekirdağ; and in the Central Anatolia Region, especially Konya and Ankara. Approximately three-quarters of the total production area is accounted for by Denizli, Uşak, Sakarya, and Antalya provinces (TÜİK, 2026).

Since 2015, support provided to growers of aromatic, medicinal, and dye plants under good agricultural practices, along with the regulation enacted in 2017 regarding the leasing of state-owned lands for medicinal and aromatic plant production, has led to a rapid increase in production areas of these crops. Indeed, between 2015 and 2025, cultivation areas increased 28-fold for sage, 15-fold for lavender, 12-fold for black cumin, and approximately two-fold for thyme (TÜİK, 2026). With the acceleration of cultivated production, the need for varieties with broad adaptability and high stability for the production of high-yield and high-quality crude drugs has increased (Turgut et al., 2023).

This study was conducted to determine the effects of harvesting at different times of the day on the biochemical properties of sage (***Salvia officinalis*** L.), an important medicinal and aromatic plant, through variables evaluated within the scope of ontogenetic variability. In addition, this research constitutes a part of a thesis study.

2.Material And Methods

The plant material used in this study was *Salvia officinalis* L., grown in 2024 at the Medicinal and Aromatic Plants Garden of Van Yüzüncü Yıl University. Immediately before harvest, in vivo and non-destructive measurements of leaf chlorophyll (µg/cm²), nitrogen balance index (NBI) (mg g^{-1}), flavonol, and anthocyanin contents (dx) were performed using a Dualex Scientific+ device (FORCE-A, France), which enables real-time assessment. Measurements were carried out using the leaf clip sensor attached to the device. All measurements were conducted with five replications, and the obtained data were statistically evaluated according to a Randomized Complete Block Design. Figure 1 shows an image from a sage plantation.



Figure 1. An image from the experiment.

3.Results And Discussion

In this study, the nitrogen balance index (NBI; chlorophyll/phenolics) content ranged between 10.62–11.08 mg g^{-1}, chlorophyll content between 21.04–21.64 µg cm^{-2}, flavonol content between 1.95–2.01 (dx), and anthocyanin content between 0.086–0.10 (dx) (Table 1, Figure 3). Figure 2 shows Dualex measurements in sage. The Dualex™ device was developed by Goulas et al. (2004) in collaboration with FORCE-A to non-destructively measure leaf phenolic content for evaluating the correlation between plant nitrogen status and leaf optical properties. Cerovic et al. (2005) reported that phenolic compounds increase under nitrogen deficiency conditions, while chlorophyll shows an opposite response. Cartelat et al. (2005) suggested that the chlorophyll/phenol ratio, expressed as NBI, is a better indicator of leaf nitrogen concentration compared to the use of individual parameters alone (Overbeck et al., 2018).



Figure 2. An image taken during the experimental measurements.

Flavonoids, which are among phenolic compounds, are one of the most important groups of secondary metabolites and bioactive compounds in plants (Kim et al., 2003). The synthesis of these compounds is highly related to light, as they function as protective pigments against UV radiation (Li et al., 1993). Under high light conditions, a rapid increase in flavonoid biosynthesis is observed, reflecting their important role in photoprotection (Schmelzer et al., 1988; Zoratti et al., 2014). Initial results obtained by Barthod et al. (2007) showed that leaf epidermal UV absorbance measured by the Dualex™ device increases significantly with increasing light intensity. It was also stated that the data obtained from this device can be a good indicator of phenolic compound content in leaves (Overbeck et al., 2018). In a similar study, NBI values in pot marigold increased between 25.17–70.56 mg g^{-1} as a result of stress induced by endophytic bacteria (Şelem et al., 2023). Furthermore, Oral et al. (2021), in a study conducted on soybean, reported that nitrogen balance index values increased under drought stress, and plant growth-promoting bacteria further increased NBI compared to the control group, ultimately leading to early maturation.

Table 1. The effect of ontogenetic variability on some biochemical parameters in sage.

Ontogenetic Variability	Nitrogen Balance Index (NBI-mg/g)	Chlorophyll Content (µg/cm^2)	Flavonol Content (dx)	Anthocyanin Content (dx)
Pre-Flowering	10,63	21,41	2,01	0,096
Full Flowering	10,62	21,04	1,97	0,100
Post-Flowering	11,08	21,64	1,95	0,086
CV (%)	**12.17**	**13.02**	**3.47**	**16.01**

The increase in NBI together with chlorophyll is consistent with studies indicating that the chlorophyll/phenolic ratio is a strong indicator for evaluating leaf nitrogen content (Cartelat et al., 2005). On the other hand, the decrease in flavonol content with advancing development can be explained by the fact that phenolic compounds, especially flavonoids, function as UV-protective pigments in relation to light and are more intensively synthesized under stress conditions (Li et al., 1993; Schmelzer et al., 1988; Zoratti et al., 2014). It has also been reported that phenolic compounds increase under nitrogen deficiency, while chlorophyll may show an opposite trend (Cerovic et al., 2005). The highest anthocyanin content observed during full flowering may be associated with increased metabolic activity at this stage and the strengthening of photoprotective and antioxidant defense mechanisms against environmental stress factors. The increase in epidermal UV absorbance determined by the Dualex™ device with increasing light intensity, and its reflection of phenolic compound content, also supports this interpretation (Barthod et al., 2007). Therefore, the observed variations throughout developmental stages can be attributed to physiological regulations in plant nitrogen metabolism and secondary metabolite synthesis.

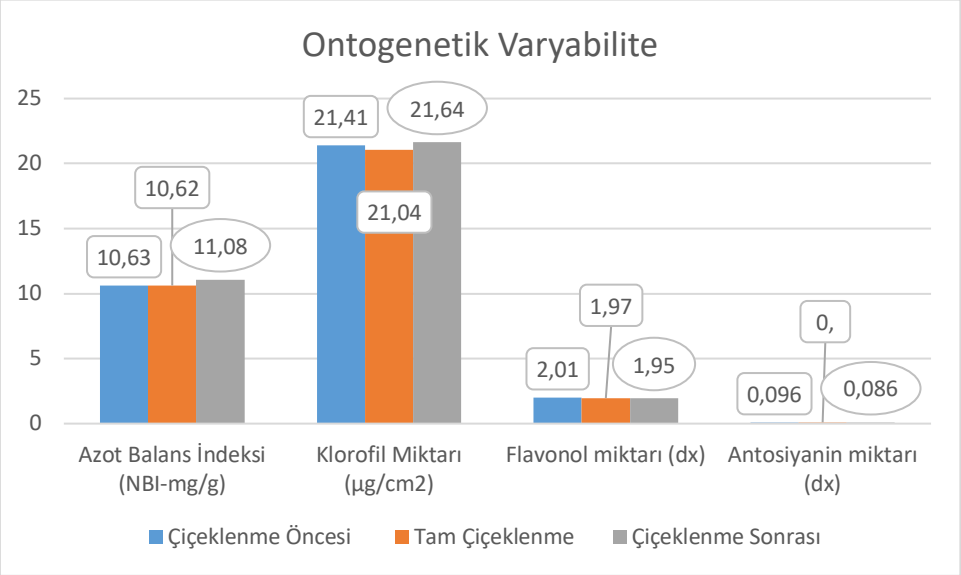


Figure 3. Mean values showing the effect of ontogenetic variability on NBI, Chl, Flv, and Ant contents in sage.

4.Conclusion

Overall, it was determined that NBI and chlorophyll values increased in the post-flowering period, whereas flavonol content showed a decreasing trend with advancing plant development. The increase in NBI, together with the rise in chlorophyll levels, indicates that the plant reorganizes its nitrogen metabolism in leaves after flowering to support photosynthesis. In contrast, the decrease in flavonol content with plant development can be attributed to the fact that flavonoids are synthesized at higher levels in early stages for UV protection, defense, and stress tolerance, while in later stages the plant allocates more metabolic resources to growth and reproductive processes. Anthocyanin content reached its highest level during full flowering and decreased in the post-flowering period. The peak in anthocyanin content at full flowering can be explained by the higher metabolic activity of the plant at this stage and the increased synthesis of anthocyanins as a protective mechanism against environmental stress factors such as high light intensity, temperature fluctuations, or oxidative stress. The reduction in anthocyanin content after flowering may be associated with reduced stress conditions, leaf senescence, and a decline in secondary metabolite production.

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DETERMINATION OF PHOTOSYNTHETIC PIGMENTS AND BIOCHEMICAL CONTENTS OF HYSSOP (*Hyssopus officinalis L.*) MICROGREENS

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Abstract:

Hyssop (***Hyssopus officinalis L.***), a member of the Lamiaceae family, is naturally distributed in the temperate regions of Asia, Europe, and America. Its essential oil is widely used in the food, pharmaceutical, and cosmetic industries. From a medicinal perspective, it has been reported to be beneficial in the treatment of digestive disorders, respiratory diseases, and women's health issues, as well as in alleviating sweating and skin irritations. Additionally, it is known to possess laxative, diuretic, and antibacterial properties and has been traditionally used in the treatment of bronchitis, cough, fungal infections, sore throat, chronic rhinitis, wounds, ulcers, and tumors.

In this study, photosynthetic pigments and biochemical contents of ***Hyssopus officinalis L.*** microgreens were evaluated. According to the results, total chlorophyll content was determined as 27.2 µg/g FW, with chlorophyll a (19.6 µg/g FW) being dominant over chlorophyll b (7.56 µg/g FW). The carotenoid content was found to be 4.75 µg/g FW. Biochemical analyses revealed that antioxidant capacity was 108.05 µmol TE/g DW, total phenolic content was 200.32 mg GAE/g DW, flavonoid content was 32.24 mg QE/100 g DW, and ascorbic acid content was 59.7 mg AsAE/100 g DW. These findings indicate that ***H. officinalis*** microgreens have significant potential as a functional food due to their high photosynthetic pigment levels and strong antioxidant and phenolic composition.

Keywords: Biochemical activity, Photosynthetic pigment, ***Hyssopus officinalis L.***, Medicinal plant

HYSSOP (*Hyssopus officinalis* L.) MİKRO YEŞİLLİKLERİNİN FOTOSENTETİK PİGMENTLER VE BİYOKİMYASAL İÇERİKLERİNİN BELİRLENMESİ

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Özet:

Zufa otu (*H. officinalis*), Lamiaceae familyasına mensup olup Asya, Avrupa ve Amerika'nın ılıman bölgelerinde doğal yayılış göstermektedir. Bitkinin uçucu yağı; gıda, farmakoloji ve kozmetik sanayinde yaygın kullanım alanı bulmaktadır. Tıbbi açıdan değerlendirildiğinde; sindirim sistemi rahatsızlıkları, solunum yolu hastalıkları, kadın hastalıklarının tedavisinde, terleme ve cilt irritasyonlarında destekleyici olarak yararlanıldığı bildirilmektedir. Bunun yanı sıra müshil, diüretik ve antibakteriyel etkilerinin bulunduğu; bronşit, öksürük, fungal enfeksiyonlar, boğaz ağrısı, kronik nezle ile yara, ülser ve tümörlerin tedavisinde geleneksel olarak kullanıldığı da bilinmektedir.

Bu çalışmada, *Hyssopus officinalis L.* mikro yeşilliklerinde fotosentetik pigmentler ile biyokimyasal içerikler birlikte değerlendirilmiştir. Elde edilen sonuçlara göre toplam klorofil 27.2 µg/g FW olup, klorofil a'nın (19.6 µg/g FW) klorofil b'ye (7.56 µg/g FW) göre baskın olduğu belirlenmiştir. Karotenoid içeriği ise 4.75 µg/g FW olarak saptanmıştır. Biyokimyasal analizler sonucunda antioksidan kapasite 108.05 µmol TE/g DW, toplam fenolik madde miktarı 200.32 mg GAE/g DW, flavonoid içeriği 32.24 mg QE/100 g DW ve askorbik asit miktarı 59.7 mg AsAE/100 g DW olarak belirlenmiştir. Elde edilen bulgular, *H. officinalis* mikro yeşilliklerinin hem yüksek fotosentetik pigment içeriği hem de güçlü antioksidan ve fenolik bileşenleri ile fonksiyonel gıda potansiyeli taşıdığını göstermektedir.

Anahtar kelimeler: Biyokimyasal aktivite, Fotosentetik pigment, *Hyssopus officinalis* L., Tıbbi bitki

1.Introduction

Hyssop (*Hyssopus officinalis* L.) belongs to the Lamiaceae family and is naturally distributed across temperate regions of Asia, Europe, and America (Güner et al., 2012). The essential oil of the plant has widespread applications in the food, pharmacology, and cosmetic industries. In addition to approximately 1% essential oil content, its chemical composition includes various bioactive compounds such as flavonoids, glycosides, tannins, and diosmin, which is why it has been used for a wide range of purposes for many years (Hatipoğlu, 2010).Today, it is mainly used in limited amounts to impart aroma and flavor to foods, and its extracts are also utilized in the beverage and food industries (Akgül, 1993). From a medicinal perspective, it has been reported to be used in the treatment of digestive disorders, respiratory diseases, and certain gynecological conditions; it is also used as a supportive remedy for sweating, skin irritations, contusions, and frostbite (Leung & Foster, 1996).In addition, it has been reported to have laxative (Öztürk & Özçelik, 1999), diuretic, and antibacterial effects, and it has traditionally been used in the treatment of bronchitis, cough, fungal infections, sore throat, chronic catarrh, as well as wounds, ulcers, and tumors (Güler, 2007; Hatipoğlu, 2010).

Hyssop (*Hyssopus officinalis*) is rich in volatile and aromatic compounds. Its essential oil contains high amounts of iso-pinocamphone, cis-pinocamphone, β-pinene, terpinen-4-ol, pinocarvone, carvacrol, p-cymene, elemol, and myrtenal. For this reason, it is widely used in the food and pharmaceutical industries (Kızıl et al., 2020). Traditionally, it has been used to treat respiratory diseases and to stimulate appetite and digestion. Hyssop also exhibits anti-inflammatory effects and has immune-modulating properties. In addition, it has been reported to reduce blood glucose levels and contribute to muscle relaxant activity, possibly due to the presence of iso-pinocamphone (tested in isolated intestinal preparations) (Leung & Foster, 1996; Newall et al., 1996).

It is projected that the world population will reach 10 billion by 2050, with approximately 70% of people living in urban areas. This situation increases the need for new and sustainable production systems capable of meeting the growing demand for food in agricultural production. Today, the agricultural sector is negatively affected by climate change, including drought, rising temperatures, and irregular rainfall, leading to reductions in yield and losses in product quality. To ensure adequate and balanced nutrition for the increasing population, fast-growing, nutrient-dense, and economically efficient agricultural products are becoming increasingly important. In this context, microgreens are considered among the new-generation production systems that offer significant agricultural advantages.

Microgreens are young plantlets of vegetables and certain herbs that are harvested shortly after the cotyledon stage and are generally produced within a short period of 7–21 days. This short production period provides producers with the advantage of rapid harvesting and continuous year-round production, making it economically significant. In addition, microgreen cultivation requires minimal space, offering great opportunities especially for urban agriculture.

Through vertical farming systems, multi-layer production can be carried out inside buildings, significantly increasing yield per unit area. By using LED lighting, climate-controlled environments, and soilless cultivation techniques, microgreen production can be carried out independently of natural environmental conditions. This reduces the risks of climate change on agricultural production, contributing to a safer and more sustainable production model.

Since microgreens can be produced from a wide variety of plant species, they also provide diversity and market advantages for producers. Many species such as cress, arugula, radish, broccoli, basil, lettuce, and parsley can be used as microgreens. Because microgreen production is fast, efficient, and suitable for mass production, it is considered a strategic production area for future food security. One of the most important requirements for successful production in

this system is the use of high-quality seeds that ensure rapid, high, and uniform germination. Thus, microgreen production is becoming one of the strong alternatives for both agricultural productivity and sustainable urban farming.

Microgreens are a food source that has recently begun to be used in raw diets. Unlike sprouts, they are germinated under light conditions and have greater flavor diversity and leaf coloration. Microgreens are harvested after the emergence of cotyledons (seed leaves), and their young leaves are more mature than sprouts but younger than true leaves (Xiao et al., 2012). They are commonly consumed in salads, sauces, sandwiches, soups, and can also be added to beverages. They provide a rich nutritional variety for vegans and vegetarians (Renna, 2015). However, not all plants can be used as microgreens, as some may cause toxicity in individuals with allergies (Aksoy, 2017). The mineral richness of microgreens may contribute to addressing global mineral deficiencies in human nutrition (Islam et al., 2020).

Some studies have shown that microgreens contain higher levels of carotenoids, vitamins (C, K, and E), minerals (Ca, Zn, Fe, Mg, Mo, Mn, and Se), and ascorbic acid, while having lower nitrate levels compared to grains and mature plants (Xiao et al., 2012). The aim of this study is to determine the biochemical content of hyssop (*Hyssopus officinalis*) microgreens, an important medicinal plant, and to expand its potential applications.

2.Material And Methods

In the experiment, the seeds were sown by lightly pressing them into a mixture of sterilized peat, cocopeat (coconut husk), and perlite obtained from a certified commercial company, filling two-thirds of a 500 cm^3 plastic container. The seeds were then covered with the same mixture to a depth of 2 cm and gently pressed down. As shown in Figure 1,2 images from microgreen production are presented.











Figure 1. Images from microgreen production.

The prepared material was placed in a fully controlled climate chamber, as described in the literature, and grown under conditions of 21 ± 2 °C / 17 ± 2 °C temperature, 50–60% humidity, and a 16/8 h light/dark photoperiod. The plants were sprayed daily with an adequate amount of distilled water. Microgreen harvesting was carried out on the 15th day. For sampling, after performing the necessary measurements on leaves using a chlorophyll sensor device (Dualex, Force-A, Paris, France), the microgreens were cut at the soil surface using sterile scissors. Total chlorophyll, chlorophyll a (CHLa), chlorophyll b (CHLb), and carotenoid (CAR) contents were determined based on fresh weight (FW) according to the method described by Lichtenthaler and Wellburn (1983). Total phenolic compounds, flavonoids, ascorbic acid, and antioxidant contents of the microgreens were measured on a dry matter (DM) basis using methods consistent with previous studies (Djordjevic et al., 2011; Niroula et al., 2019b).

The experimental data were analyzed using analysis of variance (ANOVA) according to a randomized plot design. Statistical analyses were performed based on three replications using CoStat version 6.303 (CoHort Software, Birmingham, UK). Differences between mean values were determined using the Least Significant Difference (LSD) test.

3.Results And Discussion

In the study, total chlorophyll content was determined as 27.2 µg/g FW, chlorophyll a as 19.6 µg/g FW, chlorophyll b as 7.56 µg/g FW, and carotenoid content as 4.75 µg/g FW (Table 1). In a study conducted by Sharifi-Rad et al. (2016), chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents in *Hyssopus officinalis* were reported in the ranges of 190–620, 170–360, 360–980, and 180–420 µg/g fresh weight (FW), respectively. These values are considerably higher than those obtained in the present study. It was observed that these values were lower in microgreens. However, despite the very short cultivation period, it was demonstrated that these compounds were present at significant levels in microgreens.

Table 1. Photosynthetic pigment content in microgreens of *Hyssophus officinalis* L.

Parameters	***Hyssophus officinalis* L.**
Toplam klorofil (µg/g FW)	27.2 ± 3.100
Klorofil a (µg/g FW)	19.6 ± 2.467

Klorofil b (µg/g FW)	7.56 ± 0.437
Karotenoid (µg/g FW)	4.75 ± 0,457

In our study, the NBI value was determined as 48.7 mg/g, chlorophyll content as 26.8 µg/cm², flavonol content as 0.55 dx, and anthocyanin content as 0.01 dx (Table 2). In a related study conducted by Tunçtürk and Tunçtürk (2024) on ***Arctium lapa***, the NBI (chlorophyll/phenolic) content was reported as 14.0 mg/g, chlorophyll content as 14.26 µg/cm², flavonol content as 2 (dx), and anthocyanin content as 0.067 (dx). It is noteworthy that both NBI and chlorophyll contents reported in their study were lower than those obtained in our study.

Table 2. Dualex Values in Microgreens of *Hyssophus officinalis* L.

Parameters	***Hyssophus officinalis* L.**
Nitrogen balance index (mg/g)	48.7 ± 2.54
Klorofil (µg/cm2)	26.8 ± 2.85
Flavonol (Dualex value)	0.55 ± 0.08
Antosiyanin (Dualex value)	0.01 ± 0.01

In this study, in hyssop (zufa) microgreens, the total antioxidant capacity was determined as 108.05 µmol TE/g DW, total phenolic content as 200.32 mg GAE/g DW, total flavonoid content as 32.24 mg QE/100 g DW, and ascorbic acid content as 59.7 mg AsAE/100 g DW.

Table 3. Biochemical content of microgreens of *Hyssophus officinalis* L.

Parameters	***Hyssophus officinalis* L.**
Antioksidan (µmol TE/g DW)	108.05 ± 1.44
Fenolik (mg GAE/g DW)	200.32 ± 2.53
Flavonoid (mg QE/100g DW)	32.24 ± 0.54
Askorbik asit (mg AsAE/100 g DW)	59.7 ± 8.15

In fully developed hyssop (*Hyssopus officinalis*) plants, Vlase et al. reported total antioxidant, phenolic, and flavonoid contents as 57.39 µmol TE/mg dry weight (DW), 77.0 mg GAE/g, and 1.30 mg RE/g, respectively. In a study conducted by Fathiazad et al. (2011), the

total phenolic content of mature hyssop plants was found to range between 51 and 246 mg/g. In our study, despite a cultivation period of only 15 days, it can be stated that hyssop microgreens exhibited considerably higher results compared to their mature counterparts. However, the flavonoid content was found to be lower than the values reported by the researchers.

Microgreens are generally cultivated for a short period under controlled environmental conditions; therefore, flavonoid accumulation may remain limited. In microgreens, rapid growth processes such as cell division, water uptake, and carbon metabolism dominate during the early developmental stage. In contrast, in mature plants, defense metabolism is more active, and flavonoids tend to accumulate at later stages, primarily for functions such as UV protection, defense mechanisms, and pigmentation (e.g., anthocyanin formation).



Figure 2. Different images of microgreens

4.Conclusions

Microgreens, which are harvested and consumed at an early growth stage and have been widely accepted in world cuisines, are known to be rich in antioxidants, phenolics, flavonoids, ascorbic acid, photosynthetic pigments, and certain minerals. According to the results of this study, the importance of hyssop microgreens has been demonstrated in terms of their aroma and medicinal properties. Despite their small size, they are highly rich in nutritional components such as phytochemicals, vitamins, minerals, and dietary fiber, and they provide an almost miraculous nourishing effect. Moreover, due to their aromatic taste and vibrant colors, they have the potential to be used as a new ingredient in salads, soups, desserts, and sandwiches.

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THE EFFECT OF SALICYLIC ACID PRIMING ON GERMINATION CHARACTERISTICS OF SUGAR BEET (*Beta vulgaris*) SEEDS UNDER CADMIUM TOXICITY

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Abstract

Sugar beet (*Beta vulgaris* L.), which is among the industrial crops, meets 23% of the world's sugar demand. Sugar beet is a plant highly sensitive to heavy metal pollution. Cadmium (Cd) is considered one of the primary toxic heavy metal pollutants. Salicylic acid (SA) is anticipated to increase plant tolerance against heavy metal stress. In this study, a trial was conducted to examine the effects of SA priming (pre-treatment) on the germination characteristics of sugar beet under Cd toxicity, designed as a factorial trial in a completely randomized design with four replications. In the experiment, five different concentrations of $Cd(NO_3)_2$ (0, 2, 8, 14, and 20 mg/L) and three doses of SA (0, 0.50, and 1 mM) for priming were applied. Parameters such as germination rate, germination speed, germination index, root length, shoot length, fresh plant weight, dry plant weight, and root/shoot ratio were examined in seeds germinated in petri dishes.

The data obtained from the study demonstrated that, contrary to general toxicity expectations, Cd stress exerted a stimulatory effect on the germination rate and speed. Specifically, the highest Cd concentration of 20 mg/L led to a significant increase in germination speed (28.8%) and germination rate (29.5%) compared to the control group. In contrast, severe toxicity was observed in growth parameters; shoot length was reduced from 6.03 cm to 1.65 cm, and root length decreased from 7.36 cm to 0.89 cm due to toxicity. Fresh plant weight and root/shoot ratio were also significantly negatively affected by increasing Cd concentrations.

When evaluating the effectiveness of salicylic acid (SA) primings in mitigating these stress factors, the most successful results for shoot length, root length, fresh plant weight, and root/shoot ratio were achieved with the 1 mM SA dose. It was determined that the 1 mM SA application played a protective role in minimizing the negative effects of Cd toxicity, particularly on root development. Consequently, SA supported tolerance mechanisms by reducing physiological damage caused by Cd stress in sugar beet seedlings.

Keywords: Cd Toxicity, Sugar Beet, Salicylic Acid, Germination

KADMİYUM TOKSİSİTESİ ALTINDAKİ ŞEKER PANCARI (*Beta vulgaris*) TOHUMLARINDA SALİSİLİK ASİT ÖN UYGULAMALARININ ÇİMLENME ÖZELLİKLERİNE ETKİSİ

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Özet

Endüstri bitkileri arasında yer alan şeker pancarı (*Beta vulgaris* L.) dünyanın şeker ihtiyacının %23'ü karşılamaktadır. Şeker pancarı, ağır metal kirliliğine karşı oldukça duyarlı bir bitkidir. Kadmiyum (Cd), başlıca ağır metal toksik kirleticilerden biri olarak kabul edilmektedir. Salisilik asitin (SA), ağır metal stresine karşı bitkilerin toleransını arttırdığı öngörülmektedir. Bu çalışmada şeker pancarında Cd toksisitesine karşı SA priming (ön uygulama) uygulamasının çimlenme özelliklerini incelemek üzere kurulan deneme, tesadüf parsellerinde faktöriyel deneme desenine göre 4 tekerrürlü olacak şekilde yürütülmüştür. Denemede, $Cd(NO_3)_2$ 5 farklı konsantrasyonu (0, 2, 8, 14 ve 20 mg/L) ve priming uygulaması için 3 SA dozunda (kontrol 0, 0.50 ve 1 mM) uygulama yapılmıştır. Petri kaplarında çimlendirilen tohumlarda çimlenme oranı, çimlenme hızı, çimlenme indeksi, kök uzunluğu, gövde uzunluğu, yaş bitki ağırlığı, kuru bitki ağırlığı ve kök/gövde oranı incelenmiştir.

Çalışmadan elde edilen veriler, genel toksisite beklentilerinin aksine, Cd stresinin çimlenme oranı ve hızı üzerinde uyarıcı bir etki yarattığını göstermiştir. Özellikle 20 mg/L'lik en yüksek Cd konsantrasyonu, kontrol grubuna kıyasla çimlenme oranında (%29.5) ve çimlenme hızında (%28.8) önemli bir artışa yol açmıştır. Buna karşın, büyüme parametrelerinde şiddetli bir toksisite gözlemlenmiştir. Gövde uzunluğu toksisite nedeniyle 6.03 cm'den 1.65 cm'ye, kök uzunluğu ise 7.36 cm'den 0.89 cm'ye kadar geriletmiştir. Yaş bitki ağırlığı ve kök/gövde oranı da artan Cd konsantrasyonlarından önemli anlamda olumsuz etkilenmiştir.

Salisilik asit (SA) ön uygulamalarının bu stres faktörlerini hafifletmedeki etkinliği incelendiğinde; gövde uzunluğu, kök uzunluğu, yaş bitki ağırlığı ve kök/gövde oranı bakımından SA ön uygulamaları arasında en başarılı sonuçlara 1 mM SA dozunda ulaşılmıştır. Cd toksisitenin özellikle kök gelişimi üzerindeki olumsuz etkilerini minimize etmede 1 mM SA uygulamasının koruyucu bir rol oynadığı belirlenmiştir. Sonuç olarak SA, şeker pancarı fidelerinde Cd kaynaklı fizyolojik hasarı azaltarak bitkinin tolerans mekanizmalarını desteklemiştir.

Anahtar Kelimeler: Cd Toksisitesi, Şeker Pancarı, Salisilik Asit, Çimlenme

1. Giriş

Şeker pancarı (*Beta vulgaris*), iki yıllık bir bitkidir, ancak şeker üretimi için kullanılan depolama kökü ilk yılda oluşur ve şeker üretimi için önemli bir kaynak görevi görür (Hoffmann ve ark., 2021). Şeker kamışının aksine, şeker pancarı serin iklimli bölgelerde yetiştirilmeye daha uygundur (Eggleston ve ark., 2026). Dünya şeker üretiminin yaklaşık %77'si şeker kamışından, %23'ü ise şeker pancarından elde edilmektedir (Nedić, 2015). Türkiye'de şeker üretimi şeker pancarı ile gerçekleştirilmekte olup, 2024 yılında 22,4 milyon ton üretime ulaşılmıştır (TÜİK, 2025).

Bitkiler genellikle geçici veya uzun süreli stres oluşturan toksik metallere maruz kalmaktadır. Bu stres; bitki boyu, çimlenme oranı, kök-gövde uzunluğu, biyokütle miktarı gibi büyüme parametrelerinde azalma ile kendini göstermektedir (Påhlsson, 1989). Arsenik, kadmiyum, krom, kurşun ve cıva insan sağlığı açısından önemli olan öncelikli metaller arasında yer almaktadır (Tchounwou ve ark., 2012). Ağır metal kaynaklı toksisiteye karşı bitkinin toleransı bitkinin türüne, elemente, stres süresine ve strese maruz kalan bitkinin doku veya organ yapısına bağlı olarak değişmektedir (Stresty and Madhava Rao, 1999). Cd, başlıca ağır metal toksik kirleticilerden biri olarak kabul edilir (Järup ve Akesson, 2009). Toprak Kirliliği Kontrol Yönetmeliğine göre kadmiyumun topraklarda normal konsantrasyonları <3 mg/kg olarak belirtilmiştir (TKKY, 2005). Cd metali fosfatlı gübre, tarımsal ilaçlar, evsel çöplükler, madencilik faaliyetleri ve metal işleme endüstrilerinden çevreye salınan, topraklarda yaygın olarak görülen ve suda eriyebilen bir metaldir (Öğmen, 2004; Li ve ark., 2006; Jibril ve ark., 2017). Ağır metal stresi faktörü olan Cd, kloroz, yaprak kıvrılması ve bodurluk, bitkilerde kadmiyum toksisitesinin başlıca belirtilerindendir (Benavides ve ark., 2005). Şeker pancarında morfolojik parametrelerin gerilemesine, membran bütünlüğünün bozulmasına ve ileri düzeyde hücresel ölümlere yol açarak bitki büyüme ve verimliliği kısıtlamaktadır (Haque ve ark., 2021).

SA, yüksek ve düşük sıcaklık, kuraklık, tuzluluk, ağır metal ve don stresi gibi abiyotik streslerde bitkilerin toleransını artırmaktadır (Nasircilar ve ark., 2019). Exogenous salicylic acid applications as an example of molecules effective in abiotic stress tolerance in plants.). Pandey ve ark. (2013) tarafından yapılan çalışmada, Al toksisitesine karşı SA'nın iyileştirme etkisinin Ca ve Mg uygulamalarından daha etkin olduğunu bildirmiştir. Uygun SA seviyeleriyle ön işlem, Cd toksisitesi üzerinde hafifletici bir etki gösterdiği ve aşırı dozda ekzojen SA uygulamasının kadmiyumun toksik etkilerini arttırdığı belirtilmiştir (Guo ve ark., 2019). Bu araştırmalar ışığında çalışmanın amacı, şeker pancarında Cd stresine karşı farklı oranlarda salisilik asit (SA) dozlarında ön uygulama yapılarak çimlenme ve fide özelliklerine potansiyel etkinliğinin araştırılmasıdır.

2. Yöntem

Çalışma, Siirt Üniversitesi Ziraat Fakültesi Tarla Bitkileri Bölümüne ait laboratuvarda gerçekleştirilmiştir. Bitki materyali olarak yüksek kök ve şeker verimi potansiyeline sahip Picasso çeşidi kullanılmıştır (TTSM, 2021).

Deneme tesadüf parsellerinde faktöriyel deneme desenine göre 4 tekerrürlü planlanmıştır. Kadmiyum nitratın ($Cd(NO_3)_2$) 5 farklı konsantrasyonu (Kontrol 0, 2, 8, 14 ve 20 mg/L) ve priming uygulaması için 3 farklı salisilik asit dozunda (kontrol 0, 0.50 ve 1 mM) uygulama yapılmıştır.

Tohumlar öncelikle %10'luk NaOCI çözeltisi içerisinde 10 dakika bekletilip saf su ile 4 kere yıkanmıştır. Ardından kurutma kâğıdı arasında bekletilerek nemi alındıktan sonra 3 farklı

salisilik konsantrasyonunda (kontrol 0, 0.50 ve 1 mM) 25 °C'de 48 saat prime edilmiştir (Karataş ve Konuşkan, 2022). 10 cm cam petri kapları içerisinde 2 katlı kurutma kağıtları otoklavda 121 °C'de 15 dk sterilize edilmiş ve içlerine 20 adet prime edilmiş şeker pancarı tohumu yerleştirilmiştir. Stres uygulaması için 10 ml Cd çözeltisi, kontrol grubuna ise 10 ml saf su verilmiştir. Petri kapları 20 ºC'de karanlık ortamda inkübasyona bırakılmıştır. Tohumlar her gün sayılmış ve 2 mm kökçük uzunluğuna sahip tohumlar çimlenmiş kabul edilmiştir (Bayuelo-Jiménez ve ark., 2002). Deneme çimlenmenin sona erdiği 7. günde sonlandırılmıştır. Uygulamalar arasındaki farklılıklar tesadüf parsellerinde faktöriyel deneme desenine göre JMP istatistik paket program ile analiz edilmiş ve oluşan gruplamalar LSD (0.05)'e göre yapılmıştır (Kalaycı, 2005).

İncelenen Özellikler

Çimlenme oranı, çimlenen tohumların sayısı, çimlenmeye bırakılan toplam tohum sayısına oranlanarak, çimlenme hızı ise 4. gün sayımlardan elde edilen verilere göre oranlanarak elde edilmiştir (Dumlupınar ve ark., 2007). Çimlenme indeksi, ∑n/d formülü kullanılarak hesaplanmıştır (n: ilgili günde çimlenen normal fide sayısı, d: testin başlangıcından itibaren geçen gün sayısı) (Copeland ve McDonald, 2001). Kök uzunluğu, kök başlangıcından uç kısmına kadar olan mesafe cetvel yardımıyla ölçülmüştür. Gövde uzunluğu, kök başlangıcından sürgün ucuna kadar olan mesafe cetvel yardımıyla ölçülmüştür. Kök/gövde oranı, kök uzunluğunun gövde uzunluğuna oranlanmasıyla elde edilmiştir.

3. Bulgular

Çalışmada SA ve Cd uygulamaları sonucu elde edilen ortalama değerler ve oluşan gruplamalar Tablo 1-3'te verilmiştir.

Tablo 1. Cd toksisitesi altında farklı SA uygulamalarının şeker pancarında çimlenme özelliklerine ait ortalama değerler ve oluşan gruplamalar

Çimlenme Oranı (%)						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	68.75	70.00	73.75	75.00	86.25	74.75 **a**
0.5 mM	66.25	62.50	68.75	75.00	77.50	70.00 **b**
1 mM	63.75	78.75	72.50	71.25	93.75	76.00 **a**
Ortalama	66.25 **c**	70.41 **bc**	71.66 **bc**	73.75 **b**	85.83 **a**	
LSD $_{(0.05)}$	SA: 4,49*		Cd:5,80**		SAxCd: ö.d	
CV (%)	9.59					
Çimlenme Hızı (%)						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	51.25	52.50	51.25	56.25	60.00	54.25
0.5 mM	53.75	55.00	51.25	60.00	67.50	57.50
1 mM	51.25	61.25	50.00	53.75	73.75	58.00
Ortalama	52.08 **b**	56.25 **b**	50.83 **b**	56.66 **b**	67.08 **a**	
LSD $_{(0.05)}$	SA: ö.d		Cd: 5,96**		SAxCd: ö.d	

CV (%)	12.81					
Çimlenme İndeksi						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	4.93	4.82	4.50	5.02	4.69	4.79
0.5 mM	4.68	4.22	3.98	4.72	4.68	4.46
1 mM	4.09	5.75	4.62	4.27	5.32	4.81
Ortalama	4.57	4.93	4.37	4.67	4.90	
LSD $_{(0.05)}$	SA: ö.d		Cd: ö.d		SAxCd: ö.d	
CV (%)	16.32					

**: %1 seviyesinde önemli, *: %5 seviyesinde önemli, ö.d: önemli değil, CV: Varyasyon Katsayısı, LSD:

Asgari önemli farklılık, SA: Salisilik Asit, Cd: Kadmiyum, SAxCd: SA ve Cd interaksiyonu

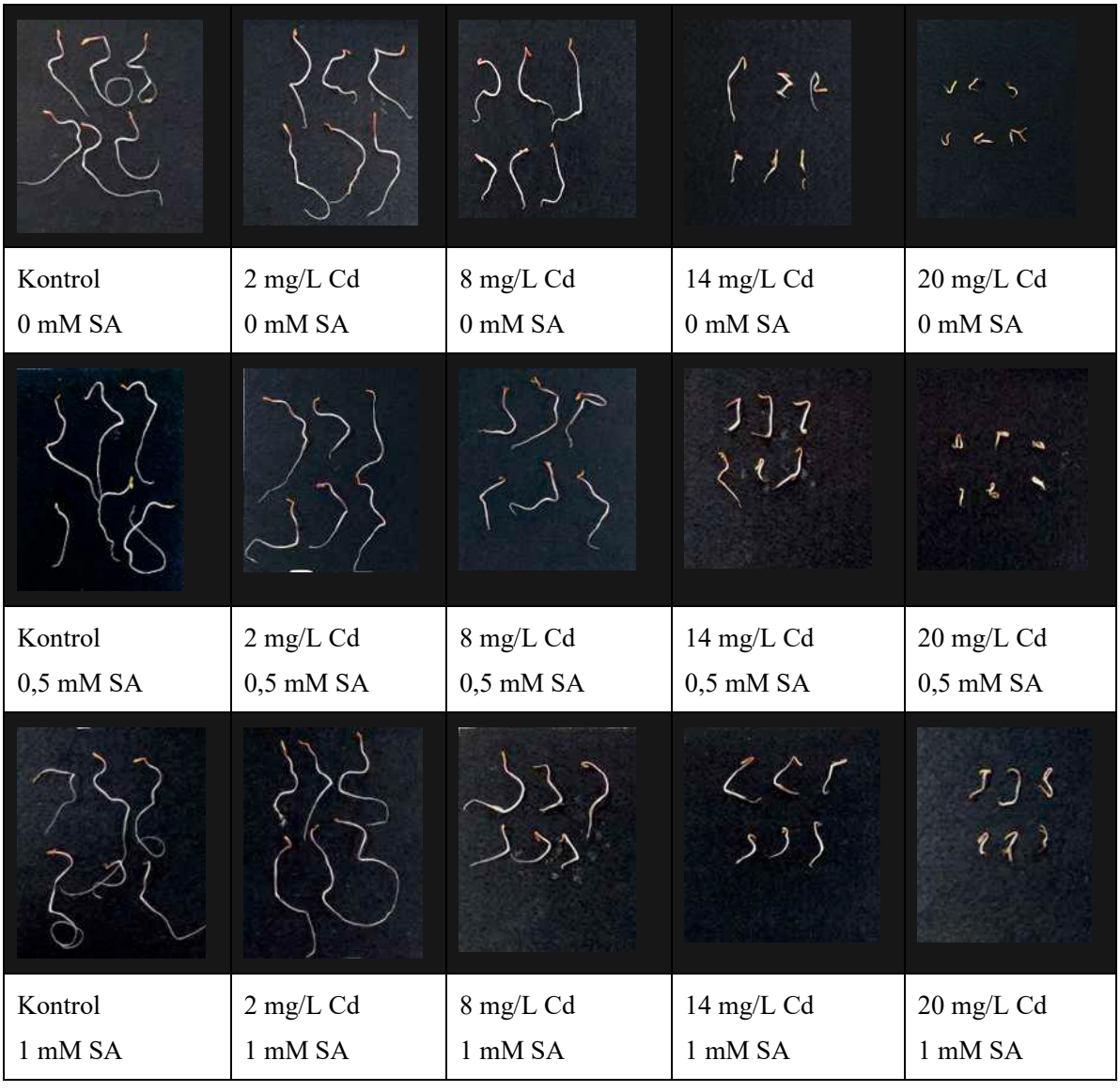
Tablo 1'e göre Cd toksisitesi çimlenme oranını kademeli olarak artırmış ve en yüksek çimlenme oranı, 1 mM SA + 20 mg/L Cd interaksiyonunda %93.75 olarak ölçülmüştür. Çimlenme hızı üzerinde Cd stresi düşük konsantrasyonlarda önemli bir etkide bulunmamıştır. Ancak yüksek dozdaki Cd (20 mg/L) çimlenme hızını en yüksek oranda (%67.08) artırmıştır. Cd stresi çimlenme indeksinde ise uygulamalar arasında önemli bir farklılık gözlenmemiştir. SA ön uygulamalarının çimlenme oranı bakımından 0.5 mM SA dozunun çimlenmeyi azalttığı, çimlenme hızı ve indeksi özellikleri bakımından ise önemli bir etkisi olmadığı gözlemlenmiştir.

Tablo 2. Cd toksisitesi altında farklı SA uygulamalarının şeker pancarında incelenen özelliklere ait ortalama değerler ve oluşan gruplamalar

Gövde Uzunluğu (cm)						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	5.76	5.80	3.94	2.56	1.15	3.84 **b**
0.5 mM	6.05	5.80	4.60	2.66	1.25	4.07 **b**
1 mM	6.28	5.91	4.70	3.03	2.56	4.49 **a**
Ortalama	6.03 **a**	5.83 **a**	4.41 **b**	2.75 **c**	1.65 **d**	
LSD $_{(0.05)}$	SA: 0.38**		Cd: 0.49**		SAxCd: ö.d	
CV (%)	14.51					
Kök Uzunluğu (cm)						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	6.35 c	5.06 d	2.62 ef	1.72 gh	0.80 ı	3.31 **c**
0.5 mM	6.88 bc	6.23 c	2.84 ef	1.83 gh	0.66 ı	3.69 **b**
1 mM	8.87 a	7.10 b	3.15 e	2.31 fg	1.20 hı	4.53 **a**
Ortalama	7.36 **a**	6.13 **b**	2.87 **c**	1.95 **d**	0.89 **e**	
LSD $_{(0.05)}$	SA: 0.32**		Cd: 0.42**		SAxCd: 0.73**	
CV (%)	13.43					
Kök/Gövde Oranı						

Salisilik Asit (SA)	Cd					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	1.10 b	0.87 cd	0.68 df	0.68 df	0.69 df	0.80 **b**
0.5 mM	1.13 b	1.07 bc	0.64 ef	0.73 de	0.52 f	0.82 **ab**
1 mM	1.40 a	1.20 b	0.67 ef	0.79 de	0.49 f	0.91 **a**
Ortalama	1.21 **a**	1.05 **b**	0.66 **cd**	0.73 **c**	0.57 **d**	
LSD $_{(0.05)}$	SA: 0.09*		Cd: 0.11**		SAxCd: 0.20*	
CV (%)	16.50					

**: %1 seviyesinde önemli, *: %5 seviyesinde önemli, ö.d,: önemli değil, CV: Varyasyon Katsayısı, LSD: Asgari önemli farklılık, SA: Salisilik Asit, Cd: Kadmiyum, SAxCd: SA ve Cd interaksiyonu



Şekil 1. Şeker pancarı tohumlarında çimlenmenin 7. gününe ait görüntüler

Cd konsantrasyonu arttıkça gövde uzunluğu, kök uzunluğu ve kök/gövde oranında kademeli olarak bir azalma olduğu görülmektedir. Gövde uzunluğu, kök uzunluğu ve kök/gövde oranı bakımından SA ön uygulamaları arasında istatistiki olarak en yüksek değere 1 mM SA

uygulamasında ulaşılmıştır (Tablo 2). Cd, şeker pancarı kök uçlarındaki hücre bölünmesinin durdurarak köklerin kahverengileşmesine neden olarak büyümeyi durdurmuştur (Şekil 1). Kök uzunluğunda Cd toksisitesinin olumsuz etkilerini azaltmada 1 mM SA uygulaması (özellikle 2 mg/L) etkin bir iyileşme sağlamıştır (Tablo 2).

Tablo 3. Cd toksisitesi altında farklı SA uygulamalarının şeker pancarında incelenen özelliklere ait ortalama değerler ve oluşan gruplamalar

Yaş Bitki Ağırlığı (mg)						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	47.05	47.00	38.30	28.75	14.10	35.04 **c**
0.5 mM	44.55	53.25	41.86	31.65	13.55	37.69 **b**
1 mM	48.65	52.80	44.90	33.25	23.60	40.29 **a**
Ortalama	47.23 **a**	49.75 **a**	43.09 **b**	31.21 **c**	17.08 **d**	
LSD $_{(0.05)}$	SA: 2.56**		Cd: **3.30		SAxCd: ö.d	
CV (%)	10,67					
Kuru Bitki Ağırlığı (mg)						
Salisilik Asit (SA)	**Cd**					
	0 mg/L	2 mg/L	8 mg/L	14 mg/L	20 mg/L	Ortalama
0 mM (Kontrol)	2.10	2.42	2.23	2.62	2.48	2.37
0.5 mM	2.37	2.47	2.55	2.64	2.46	2.50
1 mM	2.52	2.43	2.38	2.49	2.32	2.43
Ortalama	2.33	2.44	2.38	2.58	2.42	
LSD $_{(0.05)}$	SA: ö.d		Cd: ö.d		SAxCd: ö.d	
CV (%)	11.52					

**: %1 seviyesinde önemli, *: %5 seviyesinde önemli, ö.d,: önemli değil, CV: Varyasyon Katsayısı, LSD: Asgari önemli farklılık, SA: Salisilik Asit, Cd: Kadmiyum, SAxCd: SA ve Cd interaksiyonu

Yüksek Cd konsantrasyonları yaş bitki ağırlığını kademeli olarak azaltarak (kontrol) 47.23 mg'dan 17.08 mg'a kadar düşmesine neden olmuştur. SA uygulamalarında ise 1 mM ardından 0.5 SA ön uygulaması yüksek oranda etki göstererek yaş bitki ağırlığını artırmıştır. Kuru bitki ağırlığında ise uygulamalar arasında istatistiki olarak önemli bir farklılık görülmemiştir (Tablo 3).

4. Tartışma ve Sonuç

Çalışmadan elde edilen veriler, genel ağır metal toksisitesi beklentilerinin aksine, Cd stresinin şeker pancarı tohumlarının çimlenme hızı ve oranı üzerinde uyarıcı bir etki oluşturduğunu göstermiştir (Tablo 1). Çalışmayla benzer şekilde Tao ve ark. (2014), baklagiller üzerinde yürütülen çalışmada, belirli Cd dozlarının bazı türlerde çimlenmeyi engellemediği, hatta kontrol grubuna kıyasla daha yüksek çimlenme oranları sağladığı, yine Ertekin ve ark. (2020), sorgumda Cd dozlarının 400 mg/L'ye kadar çimlenme oranı ve indeksinin kontrolden

kısmen daha yüksek olduğu bildirilmiştir. Yapılan başka bir çalışmada ise 1 mM Cd uygulamasında Dinkel buğday tohumlarında çimlenme oranının arttığı daha yüksek dozlarda ise azalmaların meydana geldiği rapor edilmiştir (Küyük, 2024). Yapılan çalışmanın aksine çeltik üzerinde yapılan çalışmada, Cd konsantrasyonunun artması, tohumlarda Cd birikiminin ve çimlenme oranını önemli ölçüde azalttığı bildirilmiştir (Ahsan ve ark., 2007).

Çalışmada şeker pancarında kadmiyum nitratın çimlenme oranı ve hızını arttırmadaki etkisi; Cd bileşiğindeki nitratın çimlenmeyi teşvik etmesi veya düşük düzeydeki stresin savunma mekanizmalarını tetiklemesi (Carvalho ve ark., 2020) ile açıklanabilir. Bu durum, erken evredeki kısıtlı toksisitenin, tohumun metabolik aktivitesini baskılamak yerine çimlenmeyi uyardığını göstermektedir.

Çalışmada, Cd toksisitesinin büyüme parametrelerinde şiddetli bir inhibisyona neden olduğu gözlenmiştir. Artan Cd dozları; gövde uzunluğu, kök uzunluğu ve yaş ağırlığı bakımından önemli ölçüde azaltmıştır (Tablo 2-3). Yapılan çalışmalarda, Cd stresinin bitki yaş ağırlığı, bitki ve kök uzunluğunu önemli ölçüde azalttığı belirlenmiştir (Munzuroglu ve Geckil, 2002; Ahsan ve ark., 2007; Zhang ve ark., 2010; Tao ve ark., 2014; Liu ve ark., 2022). Kök uzunluğu gövde uzunluğuna göre Cd stresinden daha çok etkilenmiştir. Kontrol grubunda 7.36 cm olan kök uzunluğunun 20 mg/L Cd dozunda 0.89 cm'ye kadar düşmesi köklerin Cd toksisitesine karşı son derece hassas olduğunu kanıtlamaktadır (Tablo 2). Yapılan diğer çalışmalarda da kök inhibisyonunun gövdeye göre daha duyarlı olduğunu belirtmiştir (Metzger, 1992; Doğaroğlu, 2018). Bu durum, kök uçlarındaki hücre bölünmesinin Cd nedeniyle durması ve köklerin ağır metalle doğrudan temas etmesiyle açıklanabilir. Ayrıca kadmiyumun bitkilerde Reaktif Oksijen Türlerini (ROS) indükleyerek hücre ölümlerine yol açtığı belirtilmektedir (De Michele ve ark., 2009).

SA uygulamaları bitki büyümesi üzerinde önemli bir etkisi olmuştur. Özellikle 1 mM SA ön uygulaması gövde uzunluğu, kök uzunluğu, kök/gövde oranı ve yaş bitki ağırlığı bakımından olumlu bir etkisi olmuştur (Tablo 2-3). SA'nın bitki kuru ağırlık yerine bitki yaş ağırlığı artırması, muhtemelen bitkinin su stresini yönetmesine ve hücre turgorunu korumasına yardımcı olmasından kaynaklanmaktadır. Bulgular, Cd maruziyetinin bitki büyümesi üzerinde olumsuz etkisinin SA uygulamalarının etkili bir şekilde hafiflettiği belirtilen çalışmalar ile benzerlik göstermektedir (Ewais ve ark., 2015; Zulfiqar ve ark., 2024).

Sonuç olarak, Cd toksisitesi şeker pancarında çimlenme hızını ve oranını artırmıştır. Ancak, çimlenme sonrasında büyüme parametrelerinde meydana gelen kayıplar, kadmiyumun fide gelişimi için sınırlayıcı bir etkiye sahip olduğunu göstermiştir. 1 mM SA ön uygulaması, şeker pancarı fidelerinde kadmiyumdan kaynaklanan gelişimsel kayıpları azaltarak tolerans mekanizmalarını güçlendirmiştir. Bu çalışma, sürdürülebilir tarım uygulamalarında SA gibi sinyal moleküllerinin, ağır metal stresi altındaki bitkilerde koruyucu bir strateji olarak kullanılabileceğini bilimsel olarak desteklemektedir.

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RİSK TOPLUMU KURAMI ÇERÇEVESİNDE YÖNETİŞİM VE KAMU YÖNETİMİNİN DÖNÜŞÜMÜ

TRANSFORMATION OF GOVERNANCE AND PUBLIC ADMINISTRATION WITHIN THE FRAMEWORK OF RISK SOCIETY THEORY

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ÖZET

Bu çalışma, Alman sosyolog Ulrich Beck tarafından geliştirilen risk toplumu kuramını modern toplumların yapısal dönüşümü bağlamında ele almakta ve kuramın kamu yönetimi alanındaki açıklayıcı gücünü değerlendirmektedir. Beck'e göre modernlik, yalnızca refah ve üretim kapasitesini artıran bir süreç değil, aynı zamanda insan faaliyetleri sonucunda ortaya çıkan risklerin giderek yoğunlaştığı çelişkili bir toplumsal yapı üretmektedir. Nükleer tehditler, çevresel krizler, küresel salgınlar ve teknolojik dönüşümler, risk olgusunun teknik bir mesele olmaktan çıkarak toplumsal ve siyasal bir nitelik kazandığını göstermektedir. Bu bağlamda çalışma, risklerin küreselleşen yapısının kamu yönetiminde geleneksel, merkeziyetçi ve hiyerarşik karar alma mekanizmalarını nasıl dönüştürdüğünü ve yönetişim temelli, çok aktörlü ve katılımcı modellere olan ihtiyacı nasıl artırdığını tartışmaktadır. Ayrıca risklerin yalnızca nesnel tehditler değil, aynı zamanda toplumsal olarak inşa edilen algısal süreçler olduğu vurgulanmaktadır. Araştırma nitel bir yaklaşımla yürütülmüş olup literatür taramasına dayalı doküman analizi yöntemi kullanılmıştır. Çalışmada Ulrich Beck'in temel eserleri ile birlikte risk, kriz yönetimi ve yönetişim literatürü incelenmiştir. Elde edilen bulgular, risk toplumu kuramının modern kamu yönetimi anlayışını yeniden düşünmek için güçlü bir teorik çerçeve sunduğunu ve risk temelli yönetişim tartışmalarına önemli katkılar sağladığını göstermektedir.

Anahtar Kelimeler: Risk toplumu, Ulrich Beck, modernlik, risk yönetimi, yönetişim

ABSTRACT

This study examines the risk society theory developed by the German sociologist Ulrich Beck within the context of the structural transformation of modern societies and evaluates its explanatory power in the field of public administration. According to Beck, modernity is not merely a process that increases welfare and production capacity, but also a contradictory social structure in which risks generated by human activity become increasingly pervasive. Nuclear threats, environmental crises, global pandemics, and technological transformations demonstrate that risk has evolved from a purely technical issue into a social and political phenomenon. In this context, the study discusses how the globalized nature of risks transforms traditional, centralized, and hierarchical decision-making mechanisms in public administration, while simultaneously increasing the need for governance-based, multi-actor, and participatory models. It also emphasizes that risks are not only objective threats but also socially constructed perceptual processes. The research was conducted using a qualitative approach based on literature review and document analysis. The study examines Ulrich Beck's foundational works alongside literature on risk, crisis management, and governance. The findings indicate that risk society theory provides a strong theoretical framework for rethinking modern public administration and makes significant contributions to debates on risk-based governance.

Keywords: Risk Society, Ulrich Beck, Public Administration, Risk Management, Governance

GİRİŞ

Modern toplumların yapısı, özellikle 20. yüzyılın ikinci yarısından itibaren önemli bir dönüşüm sürecine girmiştir. Sanayi devrimiyle şekillenen klasik modernlik anlayışı, üretim, ilerleme ve refah artışı ekseninde gelişirken; günümüzde bu paradigma yerini giderek belirsizlik, kırılganlık ve risk üretimi ile karakterize edilen daha karmaşık bir toplumsal yapıya bırakmaktadır. Teknolojik gelişmeler, küreselleşme ve bilimsel ilerlemeler yaşamı kolaylaştırmakla birlikte, insan faaliyetlerinden kaynaklanan yeni ve öngörülemez tehdit alanlarını da beraberinde getirmiştir. Nükleer kazalar, çevresel krizler, küresel salgınlar ve dijitalleşmenin yol açtığı yapısal kırılganlıklar bu yeni risk alanlarının başlıca örnekleri arasında yer almaktadır.

Bu dönüşümü açıklamada en etkili kuramsal yaklaşımlardan biri Ulrich Beck'in risk toplumu kuramıdır. Beck, modernliğin ikinci evresinde toplumların yalnızca refahın üretimi ve dağılımı üzerinden değil, aynı zamanda risklerin üretimi, yayılımı ve yönetimi üzerinden şekillendiğini ileri sürmektedir. Bu yaklaşım, modernitenin kendi ürettiği tehditlerle yüzleşmek zorunda kaldığı refleksif modernleşme sürecine işaret etmektedir.

Risk toplumunun temel karakteristiği, risklerin giderek küresel, sınır aşan ve çoğu zaman görünmez bir nitelik kazanmasıdır. Bu durum, risklerin yönetimini yalnızca ulusal devletin kapasitesine bırakan geleneksel kamu yönetimi anlayışlarını yetersiz hâle getirmekte ve daha esnek, katılımcı ve çok aktörlü yönetişim modellerine olan ihtiyacı artırmaktadır. Bu çerçevede risk yönetimi, yalnızca kriz anlarına müdahaleyi değil, aynı zamanda önleyici politikaların geliştirilmesini, kurumsal kapasitenin güçlendirilmesini ve toplumsal güvenin yeniden inşasını da kapsamaktadır.

Bu çalışma, modern toplumun dönüşümünü Beck'in risk toplumu kuramı çerçevesinde ele alarak, kuramın kamu yönetimi disiplini açısından sunduğu teorik katkıları analiz etmeyi amaçlamaktadır. Bu doğrultuda risk kavramının dönüşümü, yönetişim anlayışındaki değişim ve çağdaş kamu politikalarına yansımaları bütüncül bir perspektifle değerlendirilmektedir.

1.ARAŞTIRMANIN YÖNTEMİ VE LİTERATÜR ÇERÇEVESİ

Bu çalışma, nitel araştırma yaklaşımı çerçevesinde tasarlanmış olup literatür temelli doküman analizi yöntemi kullanılarak yürütülmüştür. Nitel araştırmalar, toplumsal olguların bağlamı içinde derinlemesine incelenmesine imkân tanıması nedeniyle özellikle kuramsal çözümlemelerde tercih edilmektedir (Creswell, 2014). Bu doğrultuda araştırmada, risk toplumu kuramının kavramsal temelleri ile kamu yönetimi alanına yansımaları sistematik bir literatür incelemesi üzerinden değerlendirilmiştir.

Araştırmanın veri seti, Ulrich Beck'in risk toplumu kuramına ilişkin temel eserleri ile bu kuramı farklı boyutlarıyla ele alan ulusal ve uluslararası akademik çalışmalardan oluşturulmuştur. Özellikle Beck'in *Risk Society: Towards a New Modernity* (1992) adlı çalışması başta olmak üzere, modernlik ve risk ilişkisini tartıştığı eserler analiz edilmiştir (Beck, 1992; Beck, 1999). Beck'in yaklaşımı, modernliğin ikinci evresinde risklerin giderek merkezî bir konuma yerleştiğini ve bu sürecin refleksif modernleşme kavramı ile açıklanabileceğini ortaya koymaktadır.

Literatürde Beck'in kuramsal çerçevesi sıklıkla Anthony Giddens'ın modernlik ve risk ilişkisine dair çalışmalarıyla birlikte ele alınmaktadır. Giddens (1990), modern toplumlarda risk

olgusunun kurumsal yapıların ayrılmaz bir bileşeni hâline geldiğini ve bireylerin gündelik yaşam pratiklerinin risklerle iç içe geçtiğini ifade etmektedir. Benzer biçimde Lash, Szerszynski ve Wynne (1996), risk toplumunu kültürel ve toplumsal boyutlarıyla ele alarak risk algısının sosyal olarak üretildiğini vurgulamaktadır.

Kamu yönetimi literatüründe ise risk toplumu yaklaşımının özellikle yönetişim, kriz yönetimi ve sürdürülebilirlik kavramlarıyla birlikte ele alındığı görülmektedir. Pierre ve Peters (2000), geleneksel kamu yönetimi modellerinin karmaşık ve çok aktörlü risk yapıları karşısında yetersiz kaldığını belirtirken; Rhodes (1996), yönetişim perspektifinde ağ temelli yönetim yapılarının önem kazandığını ifade etmektedir. Ayrıca Boin ve 't Hart (2003), kriz yönetimi bağlamında kamu kurumlarının belirsizlik koşullarında karar alma kapasitelerinin güçlendirilmesi gerektiğine dikkat çekmektedir.

Doküman analizi sürecinde literatür tematik bir çerçevede sınıflandırılmış; risk kavramı, yönetişim, kriz yönetimi ve kamu politikaları temel başlıklar altında ele alınmıştır. Elde edilen bulgular, Beck'in risk toplumu kuramının kamu yönetimi alanında ortaya koyduğu dönüşümü açıklayıcı bir çerçevede yorumlanmıştır.

2. ANALİZ

2.1. Risk Toplumu Kuramı ve Modernliğin Dönüşümü

Modernleşme süreciyle birlikte teknolojik, ekonomik ve toplumsal alanlarda önemli dönüşümler yaşanmış; bu dönüşümler beraberinde yeni risk türlerini de ortaya çıkarmıştır. Bu bağlamda Ulrich Beck'in risk toplumu kuramı, modern toplumlarda ortaya çıkan belirsizlikleri ve insan kaynaklı tehditleri açıklayan önemli yaklaşımlardan biri olarak değerlendirilmektedir. Ulrich Beck, risk toplumunu açıklarken ikinci modernite döneminde etkili olan bazı dönüşümlere dikkat çekmektedir. Beck'e göre klasik modernleşme sürecinde ortaya çıkan dinamikler, risk toplumunda daha görünür hale gelmiş ve toplumsal yapıyı yeniden şekillendirmiştir. Bu süreçte toplumların temel sorunu yalnızca ekonomik kaynakların paylaşımı olmaktan çıkmış, aynı zamanda risklerin ve tehditlerin toplumsal dağılımı da önemli hale gelmiştir.

Bununla birlikte bireyselleşmenin artması ve çalışma yaşamının esnekleşmesi, risk toplumunun belirgin özellikleri arasında yer almaktadır. Risk toplumunda bireyler artık daha çok insan kaynaklı ve küresel etkiler doğurabilen tehlikelere karşı kaygı duymaktadır. Beck'e göre sanayi toplumunda ekonomik eşitsizlikler ön plandayken, günümüz toplumunda güvenlik ihtiyacı ve geleceğe ilişkin belirsizlikler daha merkezi bir konuma gelmiştir. Bu nedenle bireyler, öngörülemeyen risklerden korunmaya yönelik bir yaşam anlayışına yönelmektedir.

Risk toplumunun ortaya çıkardığı dönüşümler, toplumsal dayanışma biçimlerini de değiştirmiştir. Beck'e göre modern öncesi toplumlarda dayanışma daha çok ihtiyaç ve kıtlık temelinde şekillenirken, günümüz toplumlarında kaygı ve belirsizlik etrafında oluşmaktadır. Geçmişte toplumlar kıtlığa karşı örgütlenirken, günümüzde bolluk içinde olsalar bile küresel ölçekte artan riskler nedeniyle birbirine bağlıdır. Modern devletler bu riskleri sınırlamaya ve düzenlemeye çalışsa da, risk üretimi refah üretimiyle birlikte devam etmektedir. Risk toplumunda temel çatışma yalnızca servetin paylaşımı etrafında değil, aynı zamanda risklerin ve tehditlerin dağılımı etrafında şekillenmektedir. Bu riskler; sınıflar, ulusal sınırlar ve hatta kuşaklar arasında kolayca yayılabilen, öngörülmesi zor ve belirsiz nitelikte tehditlerdir (Kjaerulff, 2022).

Risk toplumu yaklaşımında riskler, geleneksel toplumlarda görülen doğal tehditlerden farklı olarak, modernleşme sürecinin ürettiği yapay ve insan kaynaklı tehditler olarak değerlendirilmektedir. Nükleer enerji, biyoteknoloji, endüstriyel üretim süreçleri ve dijitalleşme gibi alanlarda ortaya çıkan bu riskler, insan müdahalesi sonucu oluşmakta ve çoğu zaman geri döndürülemez sonuçlar doğurmaktadır (Beck, 1992; Beck, 1999). Bu çerçevede risk kavramı, teknik boyutun ötesine geçerek toplumsal olarak şekillenen ve yönetilen çok katmanlı bir olgu haline gelmektedir (Lash, Szerszynski & Wynne, 1996).

Risk toplumu teorisi, özellikle çevre, teknoloji ve modern kurumlar arasındaki ilişkiye yönelik yaklaşımları önemli ölçüde etkilemiştir. Doğal çevreyi yalnızca doğa bilimlerine ait bir alan olarak görmek yerine, çevresel sorunlara yönelik toplumsal farkındalığı modern kurumlara duyulan güvenin azalmasıyla ilişkilendirir. Bu yaklaşıma göre modernlik öncesi dönemde riskler kaçınılmaz doğal tehlikeler olarak görülürken, klasik sanayi toplumunda riskler bireylerin ve daha geniş toplumsal güçlerin eylemlerine bağlı olarak değerlendirilmiştir. Sanayi toplumu, risklerin sorumluluğunu kurumsal yapılara yükleyerek bu riskleri yönetmeye yönelik kurallar sistemi geliştirmiştir.

Sanayi toplumunda toplumsal yapının belirleyici unsuru, refahın üretimi ve sınıflar arasında dağılım iken; modernliğin ikinci evresi olarak tanımlanan risk toplumunda bu belirleyicilik, yerini giderek risklerin üretimi, dağılımı ve yönetimi süreçlerine bırakmaktadır (Beck, 1992). Bu dönüşüm, modernitenin kendi iç dinamikleri tarafından üretilen tehditlerle yüzleşmesini ifade eden "refleksif modernleşme" kavramı ile açıklanmaktadır (Beck, 1999).

Risk toplumu yaklaşımı, modernleşmeyi yalnızca bir ilerleme süreci olarak değil, aynı zamanda yeni risk alanlarının üretildiği çelişkili bir süreç olarak ele almaktadır. Beck'e göre modernleşme, gelişmeyi sağlarken aynı zamanda ekoloji, kimya ve genetik mühendisliği gibi alanlarda insan müdahalesine bağlı yeni tehditlerin ortaya çıkmasına yol açmaktadır. Bu risklerin kontrolünün giderek zorlaşması ve mevcut kurumsal mekanizmaların yetersiz kalması, risk toplumunun temel özelliklerinden biri olarak değerlendirilmektedir. Ayrıca belirsizliklerin artması ve insanlığın bu belirsizlikleri kontrol etme çabası, risk toplumunu önceki toplumsal dönemlerden ayıran en önemli unsurlar arasında yer almaktadır (Çuhacı, 2007).

Risk toplumu yaklaşımına göre günümüz bilimsel ve teknolojik gelişmelerinden kaynaklanan riskler, klasik modernite olarak ifade edilen önceki dönemlerden belirgin biçimde farklılaşmaktadır. Bu yeni riskler çoğu zaman geri döndürülemez ve birikimli nitelik taşımakta; insan duyularıyla doğrudan algılanamamakta, küresel ölçekte etkiler üretebilmekte ve ortaya çıktıkları yerden oldukça uzak coğrafyalarda sonuçlar doğurabilmektedir. Neden–sonuç ilişkilerinin belirsizleşmesi, sorumluluğun kimde olduğu tartışmasını da beraberinde getirmekte; bu durum kurumların riskleri yönetme kapasitesini zayıflatmakta ve riskleri toplumsal gruplar arasında çatışma üreten bir alana dönüştürmektedir (Benn, Brown, & North-Samardzic, 2003).

Bu bağlamda risklerin epistemolojik niteliği de dönüşmekte, riskler doğrudan gözlemlenebilir olgulardan ziyade büyük ölçüde bilimsel bilgi ve uzman değerlendirmeleri aracılığıyla tanımlanmaktadır. Ancak bilimsel bilginin hem risklerin ortaya çıkışında hem de çözümünde belirleyici rol oynaması, modern toplumlarda bilgiye ve uzmanlığa duyulan güvenin sorgulanmasına yol açmaktadır (Beck, 1992; Giddens, 1990). Bu durum, Beck'in "örgütlü sorumsuzluk" kavramı ile ifade ettiği şekilde, sorumluluğun kurumsal yapılar arasında dağılması ve giderek belirsizleşmesi sonucunu doğurmaktadır (Beck, 1999).

Öte yandan risk toplumunda risklerin dağılımı, klasik sınıf temelli eşitsizlik anlayışında önemli bir dönüşüme işaret etmektedir. Beck'e göre riskler belirli toplumsal sınıflara özgü olmasa da, risklere maruz kalma düzeyi ve bu risklerden korunabilme kapasitesi toplumsal eşitsizliklerle doğrudan ilişkilidir (Beck, 1992). Bu durum, risklerin bir yandan daha geniş toplumsal kesimlere yayılması nedeniyle "demokratikleştiği", diğer yandan ise mevcut eşitsizlikleri farklı biçimlerde yeniden ürettiği ikili bir yapı ortaya çıkarmaktadır. Bu nedenle modern toplumların analizi, yalnızca ekonomik eşitsizlikler üzerinden değil, aynı zamanda risklere maruz kalma farklılıkları üzerinden de yapılmalıdır (Giddens, 1990).

Beck'in risk toplumu yaklaşımı, modernliğin doğasına ilişkin iki temel varsayım ileri sürmektedir. İlk olarak, modern toplumların karşı karşıya olduğu risklerin önemli bir bölümünün bilinçli olarak öngörülemeyen ve "bilinmeyen bilinmezlikler" alanında yer aldığına dikkat çekilmektedir. Bu durum, bireylerin ve kurumların neyi bilmediklerini tam olarak bilememeleri nedeniyle yeni tür belirsizlikler üretmektedir. İkinci olarak ise modernitenin yarattığı bu bilgi sınırlılığı, devletlerin ve kurumların riskleri önceden tahmin etme ve kontrol etme girişimlerinin çoğu zaman yetersiz kalmasına yol açmaktadır. Üstelik bu müdahale çabaları, riskleri azaltmak yerine bireysel özgürlükler ve mahremiyet alanı üzerinde baskı oluşturarak demokratik yapıyı zayıflatma potansiyeli de taşımaktadır (Halachmi, 2015).

Giddens (1999) ise Beck'in risk toplumu düşüncesini daha da geliştirmiştir. Giddens'a göre risk toplumu, kimsenin tam olarak anlayamadığı yüksek teknoloji sınırında giderek daha fazla yaşadığımız bir toplumdur. Giddens, risk toplumunun kökenlerini "doğanın sonu" ve "geleneğin sonu" olarak adlandırdığı iki temel dönüşüme dayandırmıştır. "Doğanın sonu" ifadesi, riskin toplum için doğadan kaynaklanıp kaynaklanmadığı sorusundan, doğanın toplum tarafından nasıl risk altına sokulduğu sorusuna doğru bir yön değişimini ifade etmektedir. Tarihsel olarak doğanın topluma yönelik tehditleri, özellikle sel, kıtlık ve kuraklık gibi doğal afetlerle mücadelede devletin varlık nedenlerinden biri olmuştur. Devlet, eski dönemlerde bu tür risklerle başa çıkmanın temel aracı olarak görülmüştür (1999:3).

Şekil 1. Risk Toplumu Kuramında Modernlikten Yönetişime Geçiş



REFLEKSİF MODERNLEŞME
(Modernliğin kendini sorgulaması)

↓

KURUMSAL DÖNÜŞÜM
(Devletin rolünün değişimi)

↓

YÖNETİŞİM MODELİ
(Çok aktörlü, katılımcı, ağ temelli yapı)

↓

SONUÇ
(Risk yönetimi, şeffaflık, hesap verebilirlik, toplumsal güven)

Kaynak: Beck (1992, 1999), Giddens (1990), Lash et al. (1996) temel alınarak yazar tarafından oluşturulmuştur.

2.2. Küresel Riskler Bağlamında Yönetişim ve Risk Yönetimi Anlayışının Dönüşümü

1980'lerden itibaren, risk temelli düzenleyici yönetişime geçiş hem Avrupa'da hem Amerika'da mümkün hale gelmiş ve giderek yaygınlaşmıştır. Bu yaklaşımda risk, artık yalnızca yönetilmesi gereken bir "nesne" değil, kamu yönetiminde karar alma ve kaynak tahsisini yönlendiren bir "yöntem" olarak ele alınmaktadır. Böylece kamu kurumları, sınırlı kaynakları en yüksek risk alanlarına yönlendiren, şeffaf ve sistematik bir çerçeve içinde kanıta dayalı kararlar almaya yönelmiştir. Bu anlayış aynı zamanda devletin, zarar oluştuktan sonra müdahale eden reaktif bir yapıdan, riskleri öngörerek zarar oluşmadan önce müdahale eden proaktif bir yapıya dönüşmesini hedeflemektedir. Özellikle Çernobil, BSE krizi ve 11 Eylül gibi büyük felaketler sonrasında riskin modern toplumdaki rolü daha fazla tartışılmaya başlanmış; Ulrich Beck, Anthony Giddens, Aaron Wildavsky ve Niklas Luhmann gibi düşünürler bu alandaki teorik tartışmaları derinleştirmiştir (van der Heijden, 2021).

Risk toplumu yaklaşımı, toplumsal gelişimi aşamalar halinde ele alarak ilk aşamada risklerin geleneksel kurumlar aracılığıyla kontrol edilmeye çalışıldığını, ikinci aşamada ise artan kurumsal krizlerle birlikte daha köklü dönüşüm arayışlarının ortaya çıktığını vurgular; bu süreçte bilim ve teknoloji kaynaklı yeni belirsizlikler toplumsal ve siyasal yapıların yeniden düşünülmesini zorunlu kılarken modernitenin kendisini de tartışmalı hale getirmektedir (Benn, Brown, & North-Samardzic, 2003). Bu çerçevede, riske ilişkin karar alma süreçleri yalnızca uzmanlar ve düzenleyici kurumlarla sınırlı kalmayıp vatandaşlar, sivil toplum örgütleri ve çeşitli toplulukları kapsayacak şekilde genişlemekte; böylece risk söylemindeki hem tematik hem de aktör düzeyindeki dönüşüm, "ilk modern toplum"dan "risk toplumu"na geçişi ortaya koymaktadır.

Risk toplumu bağlamında modern toplumların yapısı yeniden tanımlanmakta; risklerin üretimi ve yönetimi, toplumsal düzenin temel belirleyici unsurlarından biri hâline gelmektedir. Bu dönüşüm, yalnızca kurumsal yapıları değil, aynı zamanda bireylerin risk algısını, toplumsal

güven düzeyini ve karar alma süreçlerini de derinden etkilemektedir. Dolayısıyla risk toplumu, modernliğin yeni paradigması olarak, toplumsal analizlerde merkezi bir konuma yerleşmektedir (Beck, 1992; Beck, 1999).

Risk toplumunun en belirgin özelliklerinden biri, risklerin küreselleşmesi olarak ortaya çıkmaktadır. Modern toplumlarda ortaya çıkan riskler, ulusal sınırları aşarak küresel ölçekte etkiler yaratmakta ve bu yönüyle "sınır tanımaz" bir nitelik kazanmaktadır. İklim değişikliği, küresel salgınlar, çevresel felaketler ve teknolojik riskler, yalnızca belirli toplumları değil, tüm insanlığı etkileyen yapısal sorunlar hâline gelmiştir (Beck, 1999; Giddens, 1990). Bu durum, risklerin yönetimini ulus-devlet düzeyinin ötesine taşıyarak çok düzeyli ve çok aktörlü bir yapıyı zorunlu kılmaktadır.

Bu küresel ve öngörülemez risklerin artışı, geleneksel hiyerarşik ve merkeziyetçi yönetim anlayışlarının yetersizliğini daha görünür hâle getirmektedir. Bu bağlamda Pierre ve Peters (2000), karmaşık ve çok boyutlu sorunların klasik kamu yönetimi araçlarıyla çözülemeyeceğini vurgularken; Rhodes (1996), bu dönüşümü yönetişim kavramı çerçevesinde açıklamakta ve yönetim süreçlerinin devlet merkezli yapıdan uzaklaşarak ağ temelli ve çok aktörlü yapılara evrildiğini ifade etmektedir.

Yönetişim yaklaşımı, risk toplumunun ortaya çıkardığı belirsizlik, karmaşıklık ve karşılıklı bağımlılık ortamına verilen kurumsal bir yanıt olarak değerlendirilmektedir (Rhodes, 1996; Pierre & Peters, 2000). Devletin tek başına riskleri yönetme kapasitesinin sınırlı olduğu bu yeni ortamda, sivil toplum kuruluşları, özel sektör aktörleri ve uluslararası örgütler karar alma süreçlerinde daha aktif rol oynamaktadır. Bu durum, yönetim süreçlerinde katılımcılık, şeffaflık ve hesap verebilirlik ilkelerinin ön plana çıkmasına neden olmaktadır.

Risk yönetiminde bütüncül yaklaşım ihtiyacı, bilgi, politika ve uygulama alanlarındaki parçalı yapıdan kaynaklanmaktadır. Risklerin genellikle sektörel ve kurumsal düzeyde ele alınması, riskler arasındaki etkileşimlerin göz ardı edilmesine yol açmakta; ayrıca farklı idari düzeyler ve bölgeler arasında risk yönetimi uygulamalarındaki çeşitlilik, ortak ve tutarlı bir yönetişim yaklaşımının geliştirilmesini zorlaştırmaktadır (Assmuth, Hildén, & Benighaus, 2010).

Risklerin öngörülemez ve gecikmeli etkiler doğuran yapısı ise yönetim anlayışını reaktif bir çerçeveden çıkararak proaktif bir niteliğe yönlendirmektedir. Bu kapsamda risk yönetimi, yalnızca kriz anlarına müdahale eden bir mekanizma olmaktan ziyade, risklerin önceden belirlenmesi, analiz edilmesi ve azaltılmasını içeren bütüncül bir politika alanına dönüşmektedir (Boin & 't Hart, 2003). Kurumsal dayanıklılık, krizlere hazırlık kapasitesi ve hızlı karar alma mekanizmaları da bu yeni yönetim anlayışının temel bileşenlerini oluşturmaktadır.

Risk toplumu yaklaşımı, kamu yönetiminde risklerin artık yalnızca teknik olarak yönetilebilen sorunlar değil, belirsiz, çok boyutlu ve insan kaynaklı süreçler olduğunu ortaya koyar. Bu durum, devletin rolünü değiştirerek merkezi ve hiyerarşik yapıdan çok aktörlü ve katılımcı bir yönetişim modeline geçişi zorunlu kılmıştır. Bu yeni yapıda kamu yönetimi yalnızca performans üretmekle değil, aynı zamanda bu performansın doğurduğu riskleri de yönetmekle sorumlu hâle gelmiştir. Dolayısıyla başarı, yalnızca çıktıların niteliğiyle değil, risklerin ne ölçüde öngörüldüğü ve kontrol edildiğiyle birlikte değerlendirilmektedir. Bu çerçevede risk toplumu, kamu yönetimini daha esnek, koordinasyon odaklı ve risk duyarlı bir

yapıya dönüştürmekte; etkin yönetim ise riskleri tamamen ortadan kaldırmaktan ziyade belirsizlikleri yönetebilme kapasitesine dayanmaktadır (Halachmi, 2015).

Bu dönüşüm doğrultusunda risk değerlendirme ve yönetim süreçleri, risklerin artan karmaşıklığı nedeniyle daha bütüncül bir perspektifle ele alınmak zorundadır. Risk entegrasyonu, risklerin yalnızca teknik boyutuyla değil; sosyal, kurumsal ve yönetsel yönleriyle birlikte değerlendirilmesini ifade etmektedir. Bu yaklaşım, kamu yönetiminde karar alma süreçlerinin yalnızca uzman temelli analizlere değil, aynı zamanda vatandaşlar, uzman topluluklar ve farklı aktörler arasındaki etkileşim ve katılıma da dayanmasını gerektirmektedir (Assmuth, Hildén, & Benighaus, 2010). Bu nedenle etkin risk yönetimi, kamu yönetiminde kurumlar arası koordinasyonun güçlendirilmesini ve farklı aktörler arasında iş birliğine dayalı, çok düzeyli ve entegre bir yönetişim anlayışının geliştirilmesini zorunlu kılmaktadır.

Beck'in "alt-politika" kavramı, geleneksel temsil mekanizmalarının dışında ortaya çıkan geçici, çok aktörlü ve esnek karar alma ağlarını ifade etmekte; çalışma grupları, danışma komiteleri ve benzeri yapılar bu yeni yönetişim biçimlerinin örnekleri olarak öne çıkmaktadır. Bu dönüşüm, kamu yönetiminde karar alma süreçlerinin hiyerarşik ve kurumsal yapılara dayalı klasik modelden uzaklaşarak daha yatay, katılımcı ve ağ temelli bir yapıya evrildiğini göstermektedir. Bu yeni yönetişim anlayışı demokratik katılımı genişletme potansiyeli taşısa da, aynı zamanda sınırları belirsiz ve sürekli yenilenen bir yönetim yapısını da beraberinde getirmektedir.

Risk toplumu yaklaşımı, modern kurumların riskleri yönetme kapasitesine duyulan güvenin azalmasıyla birlikte devlet, şirket ve hukuk gibi temel yapıların meşruiyetinde önemli bir dönüşüm yaşandığını ileri sürmektedir. Bu süreçte yönetim sorumluluğu giderek merkezden uzaklaşmakta, bireyler ve bireysel örgütler daha etkin hale gelmekte; artan bilgi ve seçenekler karşısında riskleri değerlendirme ve yönetme sorumluluğu daha fazla bireylere ve yerel aktörlere devredilmektedir. Böylece kamu yönetimi, yalnızca riskleri yöneten bir yapı olmaktan çıkıp, risk bilgisinin üretildiği ve paylaşıldığı çok aktörlü bir yönetişim alanına dönüşmektedir (Benn, Brown, & North-Samardzic, 2003).

Devletlerin hizmet sunumunu sivil toplum ve diğer aktörlerle paylaşması, katılımı artırırken yönetişim anlayışını güçlendirmektedir. Bu süreçte kamu yönetimi, hukuki, ekonomik ve kurumsal sınırlılıklar nedeniyle riskleri tek başına yönetemediğinden sivil toplum ve özel sektörle iş birliği yaparak kapasitesini genişletmektedir. Yetki devri ve dış kaynak kullanımıyla birlikte yönetim yapısı çok aktörlü bir hâl almakta ve kamu, kendi dışındaki aktörlere daha bağımlı bir konuma gelmektedir. Ancak bu dönüşüm, risk yönetimi sorumluluğunun da paylaşılmasını gerektirmekte; aksi hâlde yönetişim sürecine dâhil olan aktörlerin riskleri yeterince değerlendirmemesi kamu yararı açısından önemli sorunlar doğurabilmektedir (Halachmi, 2015).

Risklere ilişkin karar alma süreçleri ise çoğu zaman tek bir risk üzerinden değil, risklerin olası faydalarla karşılaştırıldığı ve farklı riskler arasında tercih yapılmasını gerektiren çok boyutlu bir değerlendirme çerçevesinde yürütülmektedir. Bu durum, risk değerlendirmesinin çelişen görüşler ve farklı çıkarların kesiştiği karmaşık bir alan olduğunu ortaya koymakta ve risk temelli düzenleyici yönetişimde daha kapsayıcı ve katılımcı yaklaşımlara yönelik talepleri güçlendirmektedir (van der Heijden, 2021). Katılımcı süreçler; teknik uzmanlar, bürokratik aktörler, bilim insanları ve toplumun farklı kesimlerinin bilgisini bir araya getirerek risklerin daha bütüncül biçimde değerlendirilmesini mümkün kılmakta ve yönetişimi yalnızca teknik-rasyonel bir model olmaktan çıkararak toplumsal ve siyasal boyutları olan geniş bir yapıya

dönüştürmektedir. Bununla birlikte her risk alanında geniş katılım zorunlu değildir; risklerin niteliğine bağlı olarak katılım düzeyi değişebilmektedir. Basit ve standart riskler uzmanlar tarafından yönetilebilirken, daha karmaşık ve belirsiz risklerde paydaşların ve geniş toplum kesimlerinin sürece dâhil edilmesi gerekmektedir. Bu yaklaşım hem bilgi çeşitliliğini artırmakta hem de risk altındaki aktörlerin farkındalığını güçlendirerek daha etkin risk azaltma stratejilerinin geliştirilmesine katkı sağlamaktadır.

3. TARTIŞMA VE SONUÇ

Modern toplumun geçirdiği yapısal dönüşüm, risk toplumu kuramı çerçevesinde güçlü ve açıklayıcı bir teorik zeminde değerlendirilebilmektedir. Risk toplumu yaklaşımı, modernleşmeyi yalnızca ilerleme ve refah üretimiyle sınırlı bir süreç olarak değil, aynı zamanda sistematik biçimde risk ve belirsizlik üreten çelişkili bir yapı olarak ele almaktadır. Bu çerçevede modernlik, kendi ürettiği sorunlarla yüzleşmek zorunda kalan ve sürekli kendini yeniden inşa eden refleksif bir karakter kazanmaktadır.

Risklerin küresel ölçekte yayılması, geleneksel kamu yönetimi anlayışlarının açıklayıcılığını önemli ölçüde sınırlamaktadır. Çevresel krizler, salgın hastalıklar ve teknolojik dönüşümler gibi alanlarda ortaya çıkan riskler, artık ulusal sınırlar içinde çözülebilecek sorunlar olmaktan çıkmış; çok düzeyli koordinasyon ve çok aktörlü müdahale gerektiren karmaşık bir yapıya dönüşmüştür. Bu durum, devlet merkezli yönetim anlayışının yerini ağ temelli, esnek ve iş birliğine dayalı yönetişim modellerine bırakmasını zorunlu kılmaktadır.

Risk olgusunun yalnızca fiziksel tehditlerden ibaret olmadığı, aynı zamanda toplumsal algı, güven ve bilgi süreçleri üzerinden inşa edilen sosyal bir gerçeklik olduğu da önemli bir sonuç olarak öne çıkmaktadır. Bilimsel bilginin risklerin tanımlanmasında belirleyici bir konuma gelmesi, bilgiye duyulan güvenin sorgulanmasına yol açmakta ve modern toplumlarda "güven–belirsizlik" ikilemini derinleştirmektedir. Bu bağlamda risk algısı, nesnel tehlikelerin yanı sıra toplumsal yorumlama süreçlerinden de beslenmektedir.

Risk yönetimi günümüzde yalnızca kriz anlarında devreye giren müdahaleci bir mekanizma olmaktan çıkarak, sürekli işleyen önleyici bir yönetsel kapasite alanına dönüşmüştür. Bu dönüşüm, kamu yönetiminde krizlere hazırlık, kurumsal dayanıklılık ve risk öngörüsünü merkeze alan yeni bir yönetsel yaklaşımı zorunlu kılmaktadır. Krizlerin ani, çok boyutlu ve belirsiz doğası, kamu kurumlarının daha hızlı, koordineli ve esnek karar alma mekanizmaları geliştirmesini gerektirmektedir. Bu nedenle risk ve kriz yönetimi, günümüz kamu yönetiminin yalnızca operasyonel bir alanı değil, aynı zamanda stratejik yönelimini belirleyen temel bir bileşeni haline gelmiştir.

Sonuç olarak risk toplumu kuramı, modern toplumların dönüşümünü açıklamada güçlü bir teorik çerçeve sunmaktadır. Bu kuramsal yaklaşım, modernliğin yalnızca gelişme ve kalkınma üretmediğini, aynı zamanda yeni tür belirsizlikler ve yapısal riskler de ürettiğini ortaya koyarak kamu yönetimi açısından önemli bir yeniden düşünme alanı açmaktadır. Bu yönüyle risk toplumu, günümüz yönetsel yapılarını analiz etmede ve kamu yönetiminde yaşanan dönüşümü açıklamada temel bir referans çerçevesi niteliği taşımaktadır.

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SKLERODERMALI KADINLARDA HASTALIK SÜRESİ İLE PELVİK TABAN SEMPTOMLARI VE YAŞAM KALİTESİ ARASINDAKİ İLİŞKİ

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ÖZET

Çalışmamızın amacı Sklerodermalı kadınlarda hastalık süresi ile pelvik taban semptomları ve yaşam kalitesi arasındaki ilişkiyi araştırmaktı. Çalışma yaş ortalaması 51.7 ± 4.8 yıl ve Vücut Kütle indeksi ortalaması 27.2 ± 3.6 kg/m^2 olan 65 skleroderma tanılı kadın ile tamamlandı. Katılımcıların hastalık süreleri yıl olarak, pelvik taban semptomları Pelvik Taban Distress Envanteri-20 (PFDE-20) ile, İnkontinansla ilişkili yaşam kaliteleri Pelvik Taban Etki Anketi-7 (PTEA-7) ile değerlendirildi. Çalışmadaki değişkenler Spearman Korelasyon Testi ile analiz edildi. Hastalık süresi ile POPDE-6, UDE-6 ve PTDE-20 arasında pozitif yönde orta düzey bir ilişki bulundu (sırasıyla p= .000, r= .552; p= .000, r= .551; p= .001, r= .407). Çalışmanın sonucunda Sklerodermalı kadınlarda hastalık süresi arttıkça pelvik taban semptom şiddetlerinin arttığı ve inkontinansla ilişkili yaşam kalitelerinin azaldığı bulundu. Bu durum hastalığa maruz kalma süresinin pelvik taban semptomlarını ve yaşam kalitelerini olumsuz yönde etkileyebileceğini gösterebilir.

Anahtar Kelimeler: skleroderma, pelvik taban disfonksiyonu, yaşam kalitesi.

ABSTRACT

The aim of our study was to investigate the relationship between disease duration, pelvic floor symptoms, and quality of life in women with scleroderma. The study was completed with 65 women diagnosed with scleroderma, with a mean age of 51.7 ± 4.8 years and a mean Body Mass Index of 27.2 ± 3.6 kg/m2. Disease duration was measured in years, pelvic floor symptoms were assessed using the Pelvic Floor Distress Inventory-20 (PFDI-20), and incontinence-related quality of life was assessed using the Pelvic Floor Impact Questionnaire-7 (PFIQ-7). The variables in the study were analyzed using the Spearman Correlation Test. A moderate positive correlation was found between disease duration and POPDI-6, UDI-6, and PFDI-20 (p= .000, r= .552; p= .000, r= .551; p= .001, r= .407, respectively). The study found that in women with scleroderma, the severity of pelvic floor symptoms increased and quality of life related to incontinence decreased as the duration of the disease increased. This suggests that the duration of disease exposure can negatively affect pelvic floor symptoms and quality of life.

Keywords: scleroderma, pelvic floor dysfunction, quality of life

GİRİŞ

Sistemik skleroz (skleroderma), bağ dokusunda fibrozis, vasküler hasar ve immünolojik düzensizliklerle karakterize kronik otoimmün bir hastalıktır. Hastalık; deri, gastrointestinal sistem, kas-iskelet sistemi, akciğerler ve genitoüriner sistem dahil olmak üzere birçok organ sistemini etkileyebilmektedir (Allanore ve ark., 2015). Çoğunlukla konnektif dokuyu etkileyen SSc, akciğer ve böbrek gibi organların yanında gastrointestinal sistemi ve pelvik organları da etkileyebilir (Franck-Larsson et al 2009).

Sklerodermada pelvik taban etkilenimi son yıllarda dikkat çeken klinik sorunlardan biri haline gelmiştir. Pelvik taban kasları ve bağ dokusunda gelişen fibrotik değişiklikler; üriner inkontinans, sık idrara çıkma, urgency, konstipasyon ve pelvik organ prolapsusu gibi semptomlara neden olabilmektedir. Özellikle hastalık süresinin uzamasıyla birlikte kollajen birikimi ve mikrovasküler değişikliklerin artması pelvik taban fonksiyonlarını olumsuz etkileyebilmektedir (McFarlene ve ark., 2018).

Literatürde sistemik sklerozlu bireylerde gastrointestinal ve anorektal tutulumun oldukça yaygın olduğu belirtilmektedir. Bununla birlikte üriner sistem ve pelvik taban etkilenimi gastrointestinal semptomlara kıyasla daha az araştırılmıştır. Pelvik taban semptomları kadınlarda sosyal izolasyon, fiziksel aktivite kısıtlılığı, depresyon ve yaşam kalitesinde bozulma ile ilişkili olabilmektedir (John, 2020).

Pelvik taban disfonksiyonu kronik hastalıklarda önemli bir rehabilitasyon alanıdır. Özellikle sistemik skleroz gibi progresif hastalıklarda erken dönemde pelvik taban semptomlarının belirlenmesi komplikasyonların önlenmesi açısından önem taşımaktadır. Bununla birlikte skleroderma hastalarında hastalık süresi ile pelvik taban semptomlarının ilişkisini inceleyen çalışma sayısı sınırlıdır.

Bu nedenle çalışmamızın amacı, sklerodermalı kadınlarda hastalık süresi ile pelvik taban semptomları ve yaşam kalitesi arasındaki ilişkinin incelenmesidir.

GEREÇ VE YÖNTEM

Katılımcılar

Çalışmaya sistemik skleroderma tanısı almış 65 kadın birey dahil edildi. Katılımcıların yaş ortalaması 51.7±4.8 yıl, vücut kütle indeksi ortalaması ise 27.2±3.6 kg/m² idi. Çalışmanın gerçekleşmesi için *** Üniversitesi Sağlık Bilimleri Etik kurulundan izin alındı (Decision No: 2024/714). Tüm katılımcılar çalışmaya gönüllü olarak katıldı ve çalışma Helsinki Deklarasyonu prensiplerine uygun şekilde yürütüldü.

Değerlendirmeler

Sosyodemografik Değerlendirme

Katılımcıların yaş, vücut kütle indeksi, gravida ve parite bilgileri kaydedildi. Hastalık süresi yıl olarak değerlendirildi.

Pelvik Taban Semptomlarının Değerlendirilmesi

Pelvik taban semptomları Pelvik Taban Distres Envanteri-20 (PTDE-20) kullanılarak değerlendirildi. PTDE-20; Pelvik Organ Prolapsus Distres Envanteri (POPDI-6), Kolorektal-Anal Distres Envanteri (CRADI-8) ve Üriner Distres Envanteri (UDI-6) olmak üzere üç alt boyuttan oluşmaktadır. Ölçekten elde edilen yüksek skorlar pelvik taban semptomlarının daha şiddetli olduğunu göstermektedir. PFDI-20 ve alt ölçeklerinin sınıf içi korelasyon katsayısı .96–.98'dir. PFDI-20 toplam puanı 0 ile 300 arasında değişmektedir ve yüksek puanlar, pelvik taban disfonksiyon semptomlarının şiddetinin yüksek olduğunu göstermektedir (Toprak Celenay et al., 2012).

Yaşam Kalitesinin Değerlendirilmesi

Pelvik taban semptomlarının yaşam kalitesine etkisi Pelvik Taban Etki Anketi-7 (PTEA-7) kullanılarak değerlendirildi. Ölçek fiziksel, sosyal ve emosyonel etkilenimi değerlendirmektedir. PFIQ-7'de 7 soru vardır ve her sorunun 3 ayrı yanıtı vardır. Memnuniyet, etki ve endişe maddelerinin her

birine verilen yanıt, PFIQ-7 için 3'ten (oldukça fazla) 0'a (hiç) kadar derecelendirilir. Ölçekteki yanıtlanan tüm maddelerin ortalama değeri (olası değer 0-3) tahmin edildi, ardından (100/3) ile çarpılarak 0-100 aralığındaki ölçek puanı elde edildi. PFIQ-7 net puanını (0-300 aralığı) elde etmek için 3 ölçekten alınan puanlar toplanır. Daha yüksek puan daha kötü pelvik taban disfonksiyonuna bağlı yaşam kalitesini gösterir (Balkanlı et al., 2012).

İstatistiksel Analiz

Verilerin analizinde SPSS 25.0 programı kullanıldı. Değişkenler normal dağılım gösterip göstermediklerini belirlemek için görsel (histogramlar, olasılık grafikleri) ve analitik yöntemler (Shapiro-Wilk testi) kullanılarak araştırıldı. Tanımlayıcı istatistik olarak sayısal değişkenler için ortalama ± standart sapma ve median (minimum-maksimum), kategorik değişkenler için sayı (n) ve yüzde (%) değerleri verildi. Değişkenlerin dağılımı değerlendirildikten sonra korelasyon analizlerinde Spearman Korelasyon Testi kullanıldı. İstatistiksel anlamlılık düzeyi $p<0.05$ olarak kabul edildi.

BULGULAR

Katılımcıların sosyodemografik özellikleri Tablo 1'de gösterildi.

Tablo 1. Katılımcıların Sosyodemografik ve Obstetrik Bilgileri

	Sklerodermalı Katılımcılar (n=65)
Yaş (yıl)	51.7 ± 4.8
VKI (kg/m^2)	27.2 ± 3.6
Gravida (n)	2 (1-5)
Parite (n)	2 (1-4)

n=sayı

Hastalık süresi ile pelvik taban semptomları arasındaki ilişki incelendiğinde, hastalık süresi ile POPDI-6 arasında orta düzey pozitif ilişki bulundu ($r=0.552$, $p<0.001$). Benzer şekilde hastalık süresi ile UDI-6 arasında orta düzey pozitif ilişki saptandı ($r=0.551$, $p<0.001$). Hastalık süresi ile toplam

PTDE-20 skoru arasında da anlamlı pozitif ilişki bulundu (r=0.407, p=0.001). Buna karşın hastalık süresi ile PTEA-7 arasında anlamlı ilişki saptanmadı (p>0.05).

Tablo 2. Hastalık Süresi ile Pelvik Taban Semptomları ve Yaşam Kalitesi Arasındaki İlişki

	Hastalık Süresi (yıl)	
PTEA7	r= .133	p= .289
POPDE6	r= .552	**p= .000**
CRADI8	r= .015	p= .907
UDE6	r= .551	**p= .000**
PTDE-20	r= .407	**p= .001**

PTEA7: Pelvik Taban Etki Anketi-7, POPDE6: Pelvik Organ Prolapsus Distres Envanteri, CRADI8: Kolorektal-Anal Distres Envanteri, UDE6: Üriner Distres Envanteri, PTDE: Pelvik Taban Distres Envanteri, r= Spearman Korelasyon Analizi Katsayısı

TARTIŞMA

Bu çalışmada sklerodermalı kadınlarda hastalık süresi arttıkça pelvik taban semptomlarının şiddetlendiği bulundu. Özellikle üriner semptomlar ve pelvik organ prolapsusu ile ilişkili semptomların hastalık süresiyle anlamlı ilişkili olduğu görüldü.

Sistemik sklerozda fibrotik süreçlerin ilerleyici doğası nedeniyle zaman içerisinde bağ dokusu elastikiyetinde azalma meydana gelmektedir. Pelvik taban yapılarında gelişen fibrozis, destek dokuların mekanik özelliklerini bozarak pelvik organ prolapsusu ve üriner semptomlara neden olabilmektedir (John, 2020). Çalışmamızda POPDI-6 ve UDI-6 skorlarının hastalık süresiyle ilişkili bulunması bu mekanizmayı desteklemektedir.

Sklerodermada mikrovasküler hasar ve düz kas tutulumu gastrointestinal ve genitoüriner sistem fonksiyonlarını etkileyebilmektedir. Özellikle mesane duvarında gelişen fibrotik değişikliklerin detrüsör fonksiyonlarını bozabileceği bildirilmektedir. Bunun sonucunda urgency, sık idrara çıkma ve inkontinans gibi semptomlar ortaya çıkabilmektedir (Allanore ve ark., 2015).

Çalışmamızda hastalık süresi ile yaşam kalitesi arasında anlamlı ilişki bulunmaması dikkat çekicidir. Bu durum bireylerin kronik hastalık sürecine zaman içerisinde adaptasyon geliştirmesiyle ilişkili olabilir. Bununla birlikte pelvik taban semptomlarının yaşam kalitesi üzerindeki etkisinin bireysel psikososyal faktörlerden etkilenebileceği düşünülmektedir.

Literatürde sistemik sklerozlu kadınlarda pelvik taban semptomlarının yaygın olduğu bildirilmektedir. Carvalho ve ark. (2025), sistemik sklerozlu bireylerde üriner inkontinans prevalansının genel popülasyona göre daha yüksek olduğunu belirtmiştir. Benzer şekilde Thoua ve arkadaşları (2010), gastrointestinal ve anorektal semptomların yaşam kalitesini önemli ölçüde etkilediğini bildirmiştir.

Pelvik taban disfonksiyonu rehabilitasyon açısından önemli bir klinik problemdir. Pelvik taban kas eğitimi, biofeedback uygulamaları, mesane eğitimi ve davranışsal tedavilerin üriner semptomların azaltılmasında etkili olabileceği belirtilmektedir (Bo, 2004). Bu nedenle sistemik sklerozlu kadınların rutin değerlendirmelerinde pelvik taban semptomlarının sorgulanması önem taşımaktadır.

Çalışmanın bazı sınırlılıkları bulunmaktadır. Kesitsel tasarım nedeniyle nedensellik ilişkisi kurulamaz. Ayrıca örneklem sayısının sınırlı olması sonuçların genellenebilirliğini etkileyebilir. Gelecekte daha geniş örneklemli ve longitudinal çalışmalar yapılması önerilmektedir.

SONUÇ

Sklerodermalı kadınlarda hastalık süresi arttıkça pelvik taban semptomlarının arttığı bulundu. Özellikle üriner semptomlar ve pelvik organ prolapsusu ile ilişkili şikayetlerin hastalık süresinden etkilendiği görüldü. Bu sonuçlar, sistemik sklerozlu bireylerde pelvik taban değerlendirmesinin klinik takip sürecinde önemli olduğunu göstermektedir. Multidisipliner rehabilitasyon programlarında pelvik taban rehabilitasyonuna yer verilmesi önerilmektedir.

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İŞEME DİSFONKSİYON TANILI ÇOCUKLARDA PELVİK TABAN SEMPTOMLARI, DEPRESYON DÜZEYLERİ VE YAŞAM KALİTESİ ARASINDAKİ İLİŞKİ

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ÖZET

Çalışmamızın amacı işeme disfonksiyon (İD) tanısı almış çocuklarda pelvik taban semptomları, depresyon düzeyleri ve yaşam kaliteleri arasındaki ilişkiyi araştırmaktı. Çalışmaya yaş ortalaması 11.7±1.6 olan kadın (n=56) ve erkek (n=32) İD tanılı (n=88) birey katıldı. Katılımcıların pelvik taban semptomları İşeme Bozuklukları Semptom Skoru (İBSS) ve Mesane ve Bağırsak Disfonksiyon Ölçeği (BBSS) ile; depresyon düzeyleri Çocuklar için Depresyon Ölçeği (CDI); üriner semptomların yaşam kalitelerine etkisi Üriner İnkontinanslı Çocuklarda Yaşam Kalitesi Ölçeği (PIN-Q) ile değerlendirildi. Çalışmadaki değişkenler Spearman Korelasyon Testi ile analiz edildi. Katılımcıların IBSS skoru ile PINQ-total skoru arasında orta düzey (r= .519; p= .000), CDÖ ile düşük düzey (r= .371; p= .000) pozitif bir ilişki bulundu. PINQ-içsel CDÖ arasında düşük düzeyde pozitif bir ilişki bulundu (r= .383; p= .000). BBSS ile PINQ-dışsal, PINQ-toplam ve CDÖ arasında düşük düzey pozitif bir ilişki bulundu (r= .392, r= .346, r= .372; p= .000). Dİ'li çocuklarda pelvik taban semptomları arttıkça yaşam kalitesinin azalacağı ve depresyon düzeylerinin artacağı ya da semptom şiddeti azaldıkça yaşam kalitesi artıp depresyon düzeyinin azalabileceği bulundu. Bu sonuç Dİ'li çocukların pelvik taban semptomlarının yaşam kalitesini ve psikolojik durumunu olumsuz etkileyebileceğini gösterebilir.

Anahtar Kelimeler: Disfonksiyonel İşeme, pelvik taban, depresyon, yaşam kalitesi.

ABSTRACT

The aim of our study was to investigate the relationship between pelvic floor symptoms, depression levels, and quality of life in children diagnosed with voiding dysfunction (VD). The study included 88 individuals (n=88) with VD, consisting of 56 girls and 32 boys, with an average age of 11.7±1.6 years. Pelvic floor symptoms were assessed using the Voiding Disorder Symptom Score (VDS) and Bladder and Bowel Dysfunction Scale (BBDS); depression levels were assessed using the Children's Depression Inventory (CDI); and the impact of urinary symptoms on quality of life was assessed using the Children with Urinary Incontinence Quality of Life Scale (PIN-Q). The variables in the study were analyzed using the Spearman Correlation Test. A moderate positive correlation was found between the participants' VDS score and the PINQ-total score (r= .519; p= .000), and a low positive correlation was found between the VDS score and the CDI score (r= .371; p= .000). A low positive correlation was found between PINQ-intrinsic CDI (r= .383; p= .000). A low positive correlation was found between BBDS and PINQ-extrinsic, PINQ-total, and CDI (r= .392, r= .346, r= .372; p= .000). It was found that as pelvic floor symptoms increase in children with VD, quality of life decreases and depression levels increase, or as symptom severity decreases, quality of life increases and depression levels

decrease. This result may indicate that pelvic floor symptoms in children with DI can negatively affect their quality of life and psychological well-being.
Keywords: Dysfunctional Voiding, pelvic floor, depression, quality of life.

GİRİŞ

İşeme disfonksiyonu (İD), çocukluk çağında sık görülen alt üriner sistem bozukluklarından biri olup mesane dolumu veya boşaltımı sırasında istemsiz pelvik taban kas aktivitesi, sıkışma hissi, idrar kaçırma, sık idrara çıkma ve tam boşaltamama gibi semptomlarla karakterizedir. Çocuklarda işeme disfonksiyonunun prevalansının %2 ile %25 arasında değiştiği bildirilmektedir (Austin ve ark., 2016). İşeme disfonksiyonu yalnızca üriner sistemi etkileyen bir durum olmayıp aynı zamanda çocuğun psikososyal gelişimi, sosyal katılımı, akademik performansı ve yaşam kalitesi üzerinde de önemli etkiler oluşturmaktadır (Martinelli Braga et al., 2019).

Pelvik taban kaslarının uygun olmayan aktivasyonu, işeme disfonksiyonunun temel mekanizmalarından biri olarak kabul edilmektedir. İşeme sırasında pelvik taban kaslarının gevşemesi gerekirken istemsiz kasılmanın devam etmesi mesane çıkım obstrüksiyonuna neden olabilmekte ve zamanla mesane-bağırsak disfonksiyonuna yol açabilmektedir (Lusnia ve ark., 2025). Özellikle çocuklarda görülen işeme bozuklukları, tekrarlayan üriner enfeksiyonlar, konstipasyon, gece altını ıslatma ve sosyal izolasyon gibi durumlarla ilişkilendirilmektedir (Dos Santos ve ark., 2017).

Çocukluk çağında kronik semptomlarla seyreden sağlık problemleri depresyon, anksiyete ve özgüven kaybı gibi psikolojik sorunların gelişimine zemin hazırlayabilmektedir. İşeme disfonksiyonuna bağlı semptomların çocukların sosyal yaşamını kısıtlaması, okul ortamında stres oluşturması ve akran ilişkilerini olumsuz etkilemesi nedeniyle depresif belirtilerin daha sık görülebileceği düşünülmektedir (Joinson ve ark., 2008). Bunun yanında üriner semptomların yaşam kalitesi üzerindeki etkisi son yıllarda dikkat çeken araştırma konularından biri haline gelmiştir. Yaşam kalitesi, bireyin fiziksel, psikolojik ve sosyal iyilik halini kapsayan çok boyutlu bir kavramdır. İşeme disfonksiyonlu çocuklarda idrar kaçırma, sıkışma hissi ve pelvik taban semptomları nedeniyle günlük yaşam aktivitelerinde kısıtlanma meydana gelebilmektedir. Bu durum çocukların sosyal etkinliklere katılımını azaltmakta ve yaşam doyumunu olumsuz etkileyebilmektedir (Dos Santos ve ark., 2017).

Bu çalışmanın amacı, işeme disfonksiyonu tanısı almış çocuklarda pelvik taban semptomları ile depresyon düzeyleri ve yaşam kalitesi arasındaki ilişkinin incelenmesidir.

YÖNTEM

Katılımcılar

Çalışmanın gerçekleşmesi için *** Üniversitesi Sağlık Bilimleri Etik kurulundan izin alındı (Decision No: 2025/1032) ve katılımcıların ailelerinden Helsinki deklerasyonuna uygun aydınlatılmış onam alındı. Çalışmaya işeme disfonksiyonu tanısı almış toplam 88 çocuk dahil edildi. Katılımcıların 56'sı kız (%63,63), 32'si erkek (%36,37) bireylerden oluşmaktaydı. Katılımcıların yaş (yıl), cinsiyet (kız/erkek), vücut ağırlığı (kg) ve boy uzunluğu (m) kaydedildi. Vücut Kütle İndeksleri vücut ağırlıklarını boy uzunluklarının karesine bölünerek elde edildi.

Değerlendirme Yöntemleri

Katılımcıların pelvik taban semptomları İşeme Bozuklukları Semptom Skoru (İBSS) ve Mesane ve Bağırsak Disfonksiyon Ölçeği (BBDS) kullanılarak değerlendirildi. İBSS, çocuklarda işeme sıklığı, sıkışma hissi, kesik işeme ve idrar kaçırma gibi semptomların şiddetini değerlendiren geçerli ve güvenilir bir ölçektir. İşeme Bozuklukları Semptom Skorlaması (İBSS) 2005 yılında Akbal et al. (2005) pediatrik popülasyona uyarlanmıştır. İBSS, AÜS semptomlarına yönelik 13, yaşam kalitesine yönelik 1 soru yer almaktadır. Gece idrar kaçırma ile ilgili olarak, gece idrar kaçırmanın sıklığı ve şiddeti sorgulanmaktadır. Toplam skor

0 ile 35 puan arasında değişmekte olup, skor arttıkça semptomların şiddeti artmaktadır (Akbal et al., 2005).

Mesane ve Bağırsak Disfonksiyon Ölçeği (BBDS): Çocukların mesane ve bağırsak disfonksiyonları semptomlarının şiddeti BBDS ile değerlendirildi. Bu ölçek ile mesane ve bağırsak semptomlarını değerlendirilmekte ve teşhis konulmaktadır. BBDS'nin geçerlilik ve güvenilirliği 2009 yılında Afshar et al. (2009) tarafından, Türkçe geçerlilik ve güvenilirliği ise Kaya Narter et al. (2017) tarafından yapılmıştır. Ölçek 14 sorudan oluşmaktadır. İlk 13 soru mesane ve bağırsak disfonksiyonları semptomlarına spesifiktir. Son soru ise anketin tamamlanmasının zorluk derecesini sorgulamaktadır. Her soru 5'li Likert tip olup, son soru puanlamaya eklenmemektedir. Toplam skor 0-52 arasında değişmekte ve skorun artması semptom şiddetinin arttığı anlamına gelmektedir (Narter et al.,2017).

Depresyon düzeylerinin değerlendirilmesinde Çocuklar için Depresyon Ölçeği (CDÖ) kullanıldı. CDÖ, çocuklarda depresif belirtilerin şiddetini belirlemek amacıyla yaygın olarak kullanılan özbildirim ölçeklerinden biridir. Ölçek, 6-17 yaş arasındaki çocuklara uygulanabilir. Toplam 27 maddeden oluşan ölçekte her madde için üç değişik yanıt seçeneği bulunmaktadır. Çalışmamızda çocuklardan son iki haftayı düşünmeleri ve kendileri için en uygun olan cümleyi işaretlemeleri istendi. Her cümle seti çocukluk depresyonunun belirtilerine ilişkin ifadeler içermektedir (örneğin, uyku ve iştah problemleri, disfori gibi). Maksimum puan 54'tür. Yüksek puanlar depresyon şiddetinin arttığını göstermektedir (Truby & Paxton, 2002).

Üriner semptomların yaşam kalitesine etkisi ise Üriner İnkontinanslı Çocuklarda Yaşam Kalitesi Ölçeği (PIN-Q) ile değerlendirildi. Ölçek, çocukların sosyal, emosyonel ve fiziksel yaşam alanlarında üriner semptomlardan etkilenme düzeylerini belirlemektedir. Ölçekten alınan toplam puanın artması hastanın yaşam kalitesinin kötüleştiğini göstermektedir (Saatci et al., 2025).

İstatistiksel Analiz

İstatistiksel analiz SPSS 21.00 (Statistical Package for the Social Sciences SPSS Inc, Chicago, IL) istatistik programı kullanılarak yapıldı. Sayısal değişkenler için ortalama, standart sapma, kategorik değişkenler için ise frekans ve yüzde değerleri verildi. Çalışmadan elde edilen verilerin analizinde Spearman Korelasyon Testi kullanıldı. Korelasyon katsayısının 0.00-0.25 arası çok düşük, 0.26-0.49 arası düşük, 0.50-0.69 arası orta, 0.70-0.89 arası yüksek ve 0.90-1.00 arası çok yüksek ilişkiyi gösterdiği kabul edildi. İstatistiksel anlamlılık düzeyi $p<0.05$ olarak belirlendi.

BULGULAR

Katılımcıların yaş ortalaması 11.7±1.6 yıl, VKI ortalamaları 20.2±0.8 kg/m^2, %63.33'ü kadın, %36.37'si erkekti.

Tablo 1. Katılımcıların Sosyodemografik Özellikleri

	İşeme Disfonksiyonlu Çocuklar (n=88)
Yaş (yıl)	11.7±1.6
VKI (kg/m^2)	20.2±0.8
Cinsiyet Kadın	56 (%63,63)
Erkek	32 (%36,37)

Katılımcıların İBSS skoru ile PINQ-toplam skoru arasında orta düzeyde pozitif ilişki bulundu ($r=0.519$; $p=0.000$). Bu bulgu, işeme semptomları arttıkça yaşam kalitesinin olumsuz yönde etkilendiğini göstermektedir. Ayrıca İBSS ile CDÖ arasında düşük düzeyde pozitif ilişki saptandı ($r=0.371$; $p=0.000$). Bu sonuç, işeme semptom şiddeti arttıkça depresif belirtilerin de arttığını düşündürmektedir.

PINQ-içsel alt boyutu ile CDÖ arasında düşük düzeyde pozitif ilişki bulundu (r=0.383; p=0.000). Bu durum, çocukların emosyonel yaşam kalitesindeki bozulmanın depresyon düzeyleriyle ilişkili olabileceğini göstermektedir.

BBDS ile PINQ-dışsal, PINQ-toplam ve CDÖ arasında sırasıyla düşük düzeyde pozitif ilişkiler bulundu (r=0.392, r=0.346, r=0.372; p=0.000).

Tablo 2. İşeme Disfonksiyonlu Çocuklarda Pelvik Taban Semptomları, Depresyon Düzeyleri ve Yaşam Kaliteleri Arasındaki İlişki

	IBSS	BBDQ
PINQ-Dışsal	r= .540	r= .392
	p= .000	**p= .000**
PINQ-İçsel	r= .284	r= .160
	p= .007	p= .136
PINQ-Toplam	r= .519	r= .346
	p= .000	**p= .001**
CDÖ	r= .371	r= .372
	p= .000	**p= .000**

IBSS: İşeme Bozuklukları Semptom Skoru, BBDQ: Mesane ve Bağırsak Disfonksiyon Ölçeği, PINQ: Üriner İnkontinanslı Çocuklarda Yaşam Kalitesi Ölçeği, CDI: Çocuklar için Depresyon Ölçeği,

TARTIŞMA

Bu çalışmada işeme disfonksiyonu tanılı çocuklarda pelvik taban semptomları arttıkça yaşam kalitesinin azaldığı ve depresyon düzeylerinin arttığı bulundu. Elde edilen sonuçlar literatürdeki çalışmalarla paralellik göstermektedir.

İşeme disfonksiyonu çocuklarda yalnızca fizyolojik bir problem olarak değerlendirilmemelidir. Sürekli idrar kaçırma korkusu, okul ortamında tuvalet ihtiyacının yönetilememesi ve sosyal aktiviteler sırasında yaşanan kaygılar çocukların psikolojik durumunu olumsuz etkileyebilmektedir. Joinson ve arkadaşları (2008), üriner semptomları olan çocuklarda emosyonel ve davranışsal problemlerin daha sık görüldüğünü bildirmiştir. Çalışmamızda yaşam kalitesi ile pelvik taban semptomları arasında bulunan ilişki, çocukların günlük yaşam aktivitelerinin semptomlardan önemli ölçüde etkilendiğini göstermektedir.

Pelvik taban semptomları ile depresyon düzeyleri arasında bulunan ilişki, işeme disfonksiyonunun psikolojik etkilerini desteklemektedir. Çocukluk çağında kronik sağlık problemleri bireyin özgüvenini azaltabilmekte ve sosyal çekinmeye neden olabilmektedir. Özellikle okul çağındaki çocuklarda akran ilişkileri büyük önem taşımaktadır ve üriner semptomlar çocukların sosyal kabulünü olumsuz etkileyebilmektedir.

Mesane ve bağırsak semptomlarının birlikte değerlendirilmesi de önemlidir. Literatürde konstipasyon ile işeme bozuklukları arasında güçlü ilişki olduğu belirtilmektedir (Sampaio ve ark., 2016). Bağırsak disfonksiyonunun artması pelvik taban koordinasyonunu bozarak işeme semptomlarını şiddetlendirebilmektedir.

Çalışmanın klinik açıdan önemli sonuçları bulunmaktadır. İşeme disfonksiyonlu çocukların değerlendirilmesinde yalnızca üriner semptomların değil depresyon düzeyi ve yaşam kalitesinin de değerlendirilmesi gerekmektedir. Bu nedenle çocuk ürolojisi, fizyoterapi, psikoloji ve pediatri alanlarının multidisipliner yaklaşımı önem taşımaktadır. Özellikle pelvik taban rehabilitasyonu, davranışsal tedaviler ve psikososyal destek uygulamalarının birlikte planlanması çocukların tedavi başarısını artırabilir.

Çalışmanın bazı sınırlılıkları bulunmaktadır. Çalışma kesitsel tasarımda gerçekleştirildiğinden nedensel ilişki kurulamamaktadır. Gelecekte daha geniş örneklemli ve uzun dönem takip çalışmalarının yapılması önerilmektedir.

SONUÇ

İşeme disfonksiyonlu çocuklarda pelvik taban semptomlarının artması yaşam kalitesinin azalması ve depresyon düzeylerinin yükselmesi ile ilişkili bulundu. Bu sonuçlar, işeme disfonksiyonunun yalnızca fiziksel değil aynı zamanda psikolojik ve sosyal etkileri olan çok yönlü bir sağlık problemi olduğunu göstermektedir. Çocukların değerlendirme ve tedavi süreçlerinde yaşam kalitesi ve psikolojik durumun dikkate alınması önemlidir. Multidisipliner rehabilitasyon yaklaşımlarının çocukların genel iyilik halini artırabileceği düşünülmektedir.

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DENEYSEL SEPSİS MODELLERİNDE ÇEKAL LİGASYON VE DELME YÖNTEMİNİN AVANTAJLARI

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ÖZET

Sepsis, enfeksiyona karşı gelişen düzensiz konak yanıtının, yaşamı tehdit eden organ disfonksiyonuna yol açtığı klinik bir sendromdur. Bu nedenle sepsis araştırmalarında kullanılan deneysel modellerin yalnızca inflamasyonu değil, mümkün olduğunca enfeksiyon kaynağını, konak yanıtını ve organ hasarı boyutunu da yansıtması beklenir. Güncel literatürde deneysel sepsis modelleri başlıca endotoksemi modelleri, tek patojen inokülasyon modelleri, polimikrobiyal peritonit modelleri olarak sınıflandırılmaktadır. Bu modeller arasında çekal ligasyon ve delme (CLP), polimikrobiyal abdominal sepsis oluşturması, klinik intraabdominal sepsise yakın seyir göstermesi ve yaygın kullanımı nedeniyle en sık başvurulan modellerden biri olarak öne çıkmaktadır. Bununla birlikte, hiçbir murin modelin insan sepsisinin tüm heterojenliğini tam olarak yansıtamayacağı da açıkça vurgulanmaktadır. Bu derlemede CLP yönteminin temel özellikleri, diğer deneysel sepsis modellerine göre avantajları ve sınırlılıkları, standardizasyon gereksinimleri ve hangi araştırma sorularında neden öne çıktığı kapsamlı biçimde ele alınmıştır. Sonuç olarak CLP, özellikle erişkinlerde polimikrobiyal abdominal sepsis, organ disfonksiyonu ve tedavi yanıtı araştırmaları için güçlü bir model olmaya devam etmekte; ancak neonatal sepsis, endotoksemi veya patojen-spesifik çalışmalar için alternatif modeller daha uygun olabilmektedir.

Anahtar kelimeler: Sepsis, Çekal ligasyon ve delme, Endotoksemi, Kolon ascendens stent peritonit, Çekal slurry

ADVANTAGES OF THE CECAL LIGATION AND PUNCTURE METHOD IN EXPERIMENTAL SEPSIS MODELS

ABSTRACT

Sepsis is a clinical syndrome characterized by a dysregulated host response to infection that leads to life-threatening organ dysfunction. Therefore, experimental models used in sepsis research are expected to reflect not only the inflammatory response but also, as much as possible, the source of infection, host response, and the extent of organ damage. In the current literature, experimental sepsis models are broadly classified into endotoxemia models, single-pathogen inoculation models, and polymicrobial peritonitis models. Among these, the cecal ligation and puncture (CLP) model stands out as one of the most widely used approaches due to its ability to induce polymicrobial abdominal sepsis, its close resemblance to clinical intra-abdominal sepsis, and its extensive applicability. Nevertheless, it is clearly emphasized that no murine model can fully replicate the heterogeneity of human sepsis.In this review, the fundamental characteristics of the CLP method, its advantages and limitations compared to other experimental sepsis models, the need for standardization, and the specific research contexts in which it is particularly advantageous are comprehensively discussed. In conclusion, CLP remains a robust model, particularly for investigating polymicrobial abdominal sepsis, organ dysfunction, and therapeutic responses in adult subjects. However, alternative models may be more appropriate for studies focusing on neonatal sepsis, endotoxemia, or pathogen-specific investigations.

Keywords: Sepsis, Experimental sepsis models, Cecal ligation and puncture, Endotoxemia, Colon Ascendens Stent Peritonitis, Cekal slurry

Introduction

Sepsis is defined as life-threatening organ dysfunction caused by a dysregulated host response to infection. This definition emphasizes that sepsis is neither solely an infection nor solely inflammation, but is characterized by a dysregulated host response that leads to clinically significant adverse outcomes in organ function [1]. As a direct consequence of this definition, experimental sepsis models are not expected to produce merely a short-term inflammatory stimulus. The ideal model is expected to reflect the infection focus, host response, organ dysfunction, and, if possible, specific elements of the clinical course. However, experimental modeling studies explicitly acknowledge that no perfect murine sepsis model exists. Scientists emphasize that, due to the complex and heterogeneous nature of human sepsis, the assumption of a single ideal murine model is untenable; rather, model selection should be determined based on the research question [2]. Therefore, model selection should be based on the scientific objective of the study. For example, while an endotoxemia model may be suitable for investigating acute inflammatory pathways, cecal ligation and puncture (CLP) may be a stronger option for studies on abdominal-origin polymicrobial infections and organ damage. Recent reviews comparing the advantages and limitations of experimental sepsis models also specifically highlight that researchers should choose a model based on the biological question they are addressing [3].

General Classification of Experimental Sepsis Models

Experimental sepsis models can generally be grouped under three main categories:

1. Endotoxemia models

2. Live pathogen inoculation models

3. Polymicrobial peritonitis models

This framework is commonly included in current reviews of sepsis modeling. The endotoxemia model based on LPS administration is simple and rapid; however, it does not create a true infection. Single-bacterial inoculation is suitable for examining specific pathogen-host interactions; however, it

does not represent polymicrobial sepsis. Models such as the CLP, the ascending colon stent peritonitis (CASP) model, and the cecal slurry model, however, provide higher clinical relevance, particularly for polymicrobial abdominal sepsis. It is emphasized that the cecal slurry model holds a distinct place in neonatal studies [3].

Definition and Experimental Basis of the CLP Model

The CLP model has been described as one of the most widely used animal models for investigating the pathogenesis of human sepsis for decades. It is noted that the CLP model has become a particularly preferred experimental model among many researchers due to its similarity to the characteristics of human sepsis. It is also reported that this model is widely preferred for the purpose of investigating new signaling pathways from a therapeutic perspective and better understanding the physiology of sepsis [4,5]. The basic technique of the model is based on the ligation of the cecum below the ileocecal valve and its subsequent puncture with a sterile needle. A small amount of fecal contents is then allowed to escape, and the cecum is repositioned into the abdominal cavity. This creates a source of polymicrobial infection within the abdomen [6-8].

Key Advantages of the CLP Model

The most significant advantage of the CLP is that it induces polymicrobial sepsis. Therefore, the CLP provides a biological environment that more closely mimics clinical abdominal sepsis compared to models based on a single endotoxin or a single bacterium. The purpose of the CLP method is to perforate the cecal barrier and cause peritoneal infection. Perforation of the cecum and exposure of intestinal contents lead to bacterial contamination, which in turn causes bacterial peritonitis. This is followed by bacteremia, activation of the inflammatory response, multiple organ dysfunction, and ultimately death [9]. Since it is peritonitis caused by contamination, it resembles clinical conditions such as perforated appendicitis or diverticulitis [10]. This model triggers the same immune response as seen in human sepsis. The resulting hemodynamic, inflammatory, and biochemical changes are very similar to those in human sepsis. As in human sepsis, there is a more gradual increase in plasma cytokines. The

severity of the resulting sepsis varies depending on the length of the connected tract, the size of the needle, and the number of punctures [4].

The model's greatest advantage is the simplicity of the surgical procedure. As noted above, although another significant advantage is that it closely mimics human sepsis mechanically, it has been observed that the protocols used in different laboratories vary considerably. Factors contributing to this variability include the surgeon's skill, the length of the ligated portion of the cecum, the size and number of holes in the cecum, the amount of feces expelled from the cecum, and whether or not antibiotics and fluid resuscitation are administered. An important experimental strength of the CLP is that the severity of the model can be modified by adjusting procedural details. The level of cecal ligation, needle gauge, number of perforations, and postoperative supportive therapies can all influence the outcomes. While this variability creates a standardization challenge, it also allows for the design of models representing mild, moderate, or severe sepsis [11]. Another advantage of the CLP is its widespread use in the experimental sepsis literature. This provides a crucial foundation for comparability across different research groups. This provides a crucial foundation for comparability across different research groups. Although there is an issue with full standardization, the large pool of data accumulated on the same model is valuable for biomarker, organ damage, and treatment studies [3]. Since organ dysfunction is present in sepsis, models that allow for the examination of organ damage are more clinically relevant. It is emphasized that organ/system dysfunction must be assessed using objective evidence in preclinical sepsis studies. Within this framework, CLP is among the commonly used models for investigating outcomes such as renal, pulmonary, hepatic, and microcirculatory dysfunction [4].

Comparison with Other Models

Comparison with the Lipopolysaccharide/Endotoxemia Model

The endotoxemia model is based on the injection of pure Lipopolysaccharide (LPS) and is extremely easy to administer. While this model is easy to learn and implement, it clearly has significant inherent limitations. LPS is merely a single component of the complex pathogen-associated molecular patterns

(PAMPs) structure found in Gram-negative organisms. Additionally, it excludes gram-positive organisms and polymicrobial sepsis. Most importantly, bolus LPS administration is essentially an "intoxication model" rather than a true septic condition. Therefore, while the LPS model is useful for examining early inflammatory signaling networks, it represents infection-driven sepsis more limitedly compared to the CLP model [2].

Comparison with single-pathogen inoculation models

Models based on the administration of a single bacterium or a single pathogen are suitable for investigating the virulence of a specific microorganism or the host response. However, this approach does not directly mimic polymicrobial abdominal sepsis. Studies emphasizing that model selection should be based on the research question indicate that inoculation models may sometimes be more robust than CLP for pathogen-specific questions [3].

Comparison with the Ascending Colon Stent Peritonitis Model

The Ascending Colon Stent Peritonitis (CASP) model is a polymicrobial abdominal sepsis model. Traeger and colleagues' methodological article states that CASP is a valuable model that can be applied in small animals, is highly reproducible, easy to monitor, and closely mimics the clinical condition of abdominal sepsis. In this model, a small stent is surgically placed in the ascending colon of mice or rats, leading to the continuous leakage of intestinal bacteria into the peritoneal cavity. This procedure results in peritonitis, systemic bacteremia, organ infection by intestinal bacteria, and the release of several pro- and anti-inflammatory cytokines. The lethality of CASP can be controlled by the diameter of the implanted stent. CASP is an easily learnable and highly reproducible model that closely mimics the clinical course of abdominal sepsis. Although the pathophysiological changes following CASP appear similar to those in human sepsis, the model's surgically challenging nature limits its use. The prevalence of CLP use is higher in the literature. Furthermore, many studies and reviews position CLP as the most commonly used basic model [9,12].

Comparison with the cecal slurry model

The cecal slurry model induces polymicrobial sepsis via intraperitoneal injection of cecal contents obtained from a donor animal. This model can also be used in adult mice; however, it is a significant alternative that can be considered the "gold standard" for experiments in neonatal animals. Furthermore, it is emphasized that while CLP may be technically challenging in neonates, the cecal slurry model eliminates the need for surgery and anesthesia, thereby providing a significant advantage for neonatal research. Researchers note that while cecal slurry better represents human neonatal sepsis, CLP remains the gold standard in adult sepsis studies. Therefore, the "best model" may vary depending on the age group [13].

Conclusion

The CLP's strong position in the field of experimental sepsis stems from the model's polymicrobial and infection-focused nature, its ability to mimic the course of clinical intra-abdominal sepsis, and its long-standing widespread use by researchers. Despite all these advantages, it cannot be said that the CLP is the best model under all conditions. Considering the research conducted on sepsis, no murine sepsis model fully represents the heterogeneity of human sepsis. Therefore, the choice of model in research must be based on the specific research question. For example, the cecal slurry model is more suitable for studies involving newborns. If a more pronounced modeling of continuous fecal leakage and peritoneal contamination is desired, the CASP model may be more appropriate. If only the early inflammatory response is being investigated, the endotoxemia model may be more suitable. Nevertheless, when considering adult polymicrobial abdominal sepsis, the CLP model remains the primary model of choice. The advantages of the CLP model are particularly evident in preclinical studies where organ dysfunction, the source of infection, the polymicrobial nature, and the response to treatment are examined together.

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MİSTİSİZM VE RUHSAL SAĞLIK İLİŞKİSİ ÜZERİNE DEĞERLENDİRME

AN ASSESSMENT OF THE RELATİONSHİP BETWEEN MYSTİCİSM AND MENTAL HEALTH

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ÖZET

Mistisizm, tarihsel süreç içerisinde kimi zaman irrasyonel ya da patolojik bir deneyim alanı olarak değerlendirilmiş, özellikle modern psikiyatrinin erken dönemlerinde psikotik yaşantılarla ilişkilendirilmiştir. Bununla birlikte çağdaş psikoloji ve din psikolojisi araştırmaları, mistik tecrübelerin bireyin ruhsal bütünlüğü, psikolojik dayanıklılığı ve anlam üretme kapasitesi üzerinde dönüştürücü etkiler oluşturabileceğini ortaya koymaktadır. Bu çalışma, mistisizm ile ruhsal sağlık arasındaki ilişkiyi disiplinlerarası bir perspektifle ele almayı amaçlamakta, klasik tasavvuf düşüncesi ile modern psikoloji kuramları arasında kavramsal bir karşılaştırma yapmaktadır. William James'in dini tecrübenin "noetik" ve dönüştürücü niteliğine yaptığı vurgu, Carl Jung'un bireyleşme kuramı çerçevesinde mistik deneyimi bilinçdışı ile bütünleşme süreci olarak yorumlaması ve Abraham Maslow'un zirve deneyim (peak experience) kavramı, mistisizmin benlik gelişimine katkı sağlayan yapıcı yönünü ortaya koymaktadır. Viktor Frankl'ın anlam temelli psikoterapi yaklaşımı ise, mistik yönelimin varoluşsal boşluk, kaygı ve anlamsızlık duygularının aşılmasında önemli bir işlev üstlenebileceğini göstermektedir. Tasavvuf geleneğinde nefs terbiyesi, kalp tasfiyesi ve hal–makam öğretisi bireyin içsel arınma ve denge sürecini sistematik bir gelişim modeli olarak sunmaktadır. Gazâlî ve İbnü'l-Arabî'nin ortaya koyduğu bu çerçeve, modern psikolojideki benlik bütünleşmesi, öz-farkındalık ve psikolojik iyi oluş kavramlarıyla paralellik arz etmektedir. Bu bağlamda çalışma, mistisizmin yalnızca metafizik bir tecrübe değil, aynı zamanda ruhsal iyilik hâlini destekleyen bütüncül bir dönüşüm süreci olduğunu ileri sürmektedir.

Anahtar Kelimeler: Mistisizm, Psikoloji, Ruh Sağlığı, Nefs Terbiyesi, Psikolojik İyi Oluş, Anlam Arayışı.

ABSTRACT

Mysticism has sometimes been regarded as an irrational or pathological experience within the historical process; it has been associated with psychotic experiences, particularly in the early days of modern psychiatry. However, contemporary psychology and psychology of religion studies reveal that mystical experiences can have transformative effects on an individual's spiritual integrity, psychological resilience, and capacity for meaning-making. This study aims to address the relationship between mysticism and spiritual health from an interdisciplinary perspective, making a conceptual comparison between classical Sufi thought and modern psychological theories. William James' emphasis on the "noetic" and transformative nature of religious experience, Carl Jung's interpretation of mystical experience as a process of integration with the unconscious within the framework of his theory of individuation, and Abraham Maslow's concept of peak experience reveal the constructive aspect of mysticism that contributes to self-development. Viktor Frankl's meaning-based psychotherapy approach demonstrates that mysticism can play an important role in overcoming existential emptiness, anxiety, and feelings of meaninglessness. In the Sufi tradition, self-discipline, purification of the heart, and the teaching of states and stations present the individual's process of inner purification and balance as a systematic model of development. The framework presented by Ghazali, and Ibn al-Arabi parallels the concepts of self-integration, self-awareness, and psychological well-being in modern psychology. In this context, the study argues that mysticism is not only a metaphysical experience but also a holistic transformation process that supports spiritual well-being.

Keywords: Mysticism, Psychology, Mental Health, Self-Discipline, Psychological Well-Being, Search for Meaning.

GİRİŞ

Mistisizm, insanlık tarihinin en köklü ve evrensel deneyim alanlarından biri olarak tarihsel süreç içerisinde farklı disiplinler tarafından çeşitli şekillerde yorumlanmıştır. Özellikle modern psikiyatrinin ilk dönemlerinde mistik tecrübeler sıklıkla irrasyonel, gerçeklikten kopuk ve hatta patolojik olgular olarak değerlendirilmiştir. Ancak 20. yüzyılın başlarından itibaren, özellikle William James'in öncülüğünü yaptığı çalışmalarla birlikte, mistik deneyimin insan ruhunun derinliklerinde anlam üreten, dönüştürücü ve yapıcı bir doğaya sahip olduğu gerçeği modern bilimin gündemine girmiştir.

Günümüz dünyasında birey varoluşsal boşluk, anlam kaybı ve kronik kaygı sarmalında ruhsal bir denge arayışı içerisindedir. Bu arayış, ruhsal sağlığın sadece biyolojik ve bilişsel bir "hastalık olmama" durumu değil, aynı zamanda insanın aşkın olanla kurduğu bağ ve içsel bütünleşme süreci olduğunu göstermektedir. Bu bağlamda klasik tasavvuf düşüncesindeki "nefs terbiyesi" ve "kalp tasfiyesi" gibi kavramlar, modern psikolojinin "kendini gerçekleştirme", "bireyleşme" ve "bilinçli farkındalık" (mindfulness) gibi kavramlarıyla şaşırtıcı paralellikler sergilemektedir.

Bu çalışma, mistisizm ile ruhsal sağlık arasındaki bu derin ve dinamik ilişkiyi disiplinlerarası bir perspektifle ele almayı hedeflemektedir. Modern psikoloji kuramlarının sunduğu kuramsal çerçeve ile tasavvuf düşüncesinin insan psikolojisine dair geliştirdiği sistematik modeller arasında kavramsal bir karşılaştırma yapılacaktır. Özellikle geleneksel manevî eğitim yöntemlerinin bireyin iç dünyasında nasıl bir denge oluşturduğu, modern psikoterapötik süreçlerin verileriyle sentezlenecektir.

Çalışmanın temel iddiası mistik öğretilerin ve tasavvufî pratiklerin, bireyin psikolojik dayanıklılığını artıran, duygusal düzenleme kapasitesini güçlendiren ve varoluşsal krizleri birer dönüşüm fırsatına çeviren bütüncül bir ruhsal sağlık modeli sunduğudur. Bu doğrultuda, kadim geleneklerin manevî tecrübe modelleri ile modern psikolojinin bilimsel verileri arasında kurulacak bir diyalog, insanı sadece zihinsel değil, ruhsal ve varoluşsal boyutlarıyla bir bütün olarak anlamamıza katkı sağlayacaktır.

Mistisizmde Dinsel Deneyim ve İçsel Dönüşüm

Mistisizm evrensel bir olgudur. Farklı dinî ve kültürel geleneklerde çeşitli biçimlerde ortaya çıkmakla birlikte, özünde bireyin aşkın bir gerçeklikle doğrudan temas kurma arayışını ifade eder. İslam tasavvufu, Hristiyan mistisizmi ve Doğu meditasyon gelenekleri gibi farklı sistemlerde görülen bu deneyim, biçimsel farklılıklara rağmen ortak bir içsel dönüşüm sürecine işaret eder. Bu bağlamda mistisizm, doktrinsel bilgiden ziyade deneyimsel bilgiye dayanır ve bireyin bilinç durumunda derin değişimler meydana getirmeyi amaçlar.

Modern dünyada bireyin karşı karşıya kaldığı varoluşsal boşluk, anlam kaybı ve artan kaygı düzeyi, ruhsal sağlığın yalnızca biyolojik ve bilişsel boyutlarla açıklanamayacağını ortaya koymaktadır. Nitekim Viyana okulunun kurucu düşünürlerinden olan Viktor Frankl[29], insanın temel motivasyonunun logoterapi denilen "anlam arayışı" olduğunu belirterek, bu ihtiyacın karşılanmamasının ciddi psikolojik sorunlara yol açabileceğini vurgulamaktadır. Bu bağlamda mistik ve dinî tecrübeler, bireyin anlam arayışına cevap veren önemli bir alan olarak öne çıkmaktadır.

[29] Viktor E. Frankl, İnsanın Anlam Arayışı (İstanbul: Okuyanus Yayıncılık, 2022).

Modern psikolojinin ve pragmatizmin kurucu isimlerinden olan William James özellikle dinî tecrübe, bilinç ve hakikat anlayışı kavramları üzerine yaptığı çalışmalar ile hem felsefeyi hem de psikolojiyi derinden etkilemiştir. James'e[30] göre din, ilâhî olanla doğrudan yaşanan bir tecrübedir, dinî tecrübe de kurumdan önce kişisel bir deneyimdir. The Varieties of Religious Experience'te (Dinsel Deneyimin Çeşitleri) özellikle vurguladığı paradigma kurumsal din, asıl din değildir. Asıl din dediğimiz dinin özü, bireyin aşkın olan varlıkla içsel ve kişisel tecrübesinde ortaya çıkar.

Öyle ki hakikatte din, bireyin iç dünyasında yaşanır ve kişide dönüşüm (transformation) gerçekleştirir. Bu durum, tasavvufî gelenekte veya mistisizmdeki hal ve zevk odaklı manevî terbiyeyle dikkat çekici paralellikler sunar. Nitekim bu paralellik, Mevlânâ Celâleddîn-i Rûmî'nin hakikati doğrudan yaşanan bir tecrübe olarak ele alması ve Yunus Emre'nin ilahî hakikati "tatmak" ve "yaşamak" üzerinden ifade etmesiyle somut bir şekilde görülmektedir. Bu bağlamda söz konusu tecrübe, bireyin ahlâkî ve ruhsal dönüşümünü hedefleyen bir terbiye sürecinin de temelini oluşturmaktadır.

Yunus Emre'nin en önemli aforizmalarında olan "ilim ilim bilmektir, ilim kendin bilmektir" yaklaşımı bilginin teorik bir birikimden ziyade, bireyin kendi varlığında tecrübe ettiği bir hakikat olduğunu göstermekte, bu da William James'in dini bireysel dinsel deneyim olarak temellendirdiği yaklaşımıyla örtüşmektedir. Bu çerçevede dinsel deneyim, tasavvuf düşüncesinde hal ve zevk kavramları ile karşılık bulmakta ve William James'in de vurguladığı üzere hakikatin ancak bireysel ve doğrudan tecrübe yoluyla elde edilebileceğini ortaya koymaktadır.

Mistisizmin Ruhsal Sağlık Üzerindeki Etkileri

Mistisizm, bireyin yalnızca metafizik bir arayış içerisinde olmasını değil, aynı zamanda ruhsal dengesi üzerinde doğrudan etkiler oluşturan bir deneyim alanını ifade etmektedir. Bu bağlamda mistik tecrübe, bireyin iç dünyasında meydana getirdiği dönüşüm aracılığıyla ruhsal sağlığı destekleyen önemli bir unsur olarak değerlendirilebilir. Modern psikoloji alanında yapılan çalışmalar, spiritüel ve mistik yönelimi yüksek bireylerin stres, kaygı ve depresyon gibi psikolojik sorunlarla daha etkin bir şekilde başa çıkabildiğini ortaya koymaktadır. Bu durum, mistik deneyimin bireyin duygusal düzenleme kapasitesini artırdığını ve psikolojik dayanıklılığını güçlendirdiğini göstermektedir. Özellikle Viktor Frankl'ın ortaya koyduğu üzere, insanın temel motivasyonu anlam arayışıdır. Mistik tecrübe, bireyin varoluşuna anlam kazandırarak bu ihtiyacı karşılamakta ve böylece varoluşsal boşluk hissini azaltmaktadır. Anlam duygusunun güçlenmesi ise bireyin ruhsal dengesini korumasında belirleyici bir rol oynamaktadır. Bunun yanı sıra mistik pratikler, bireyin zihinsel süreçlerini düzenleyerek içsel bir huzur ve denge hali oluşturmasına katkı sağlamaktadır. Meditasyon, zikir ve benzeri uygulamalar dikkat ve farkındalık düzeyini artırmakta, bu durum da bireyin stresle başa çıkma kapasitesini güçlendirmektedir. Bu yönüyle mistik deneyim, modern psikolojide "mindfulness" olarak ifade edilen bilinçli farkındalık süreçleriyle önemli ölçüde benzerlik göstermektedir.

[30] William James, Dinsel Deneyimin Çeşitleri (İstanbul: Pinhan Yayıncılık, 2017).

Tasavvuf geleneği özelinde değerlendirildiğinde, mistisizmin ruhsal sağlık üzerindeki etkileri daha sistematik bir biçimde ortaya konulmaktadır. Tasavvufa göre insanın temel problemi, nefsin hâkimiyeti ve kalbin kirlenmesi olup, ruhsal sorunlar yalnızca psikolojik değil aynı zamanda manevî bir dengesizlik olarak ele alınmaktadır. Bu çerçevede İmam Gazâlî, kalp hastalıklarını analiz ederek bireyin iç dünyasını arındırmaya yönelik yöntemler geliştirmiştir. Tasavvufî pratikler arasında yer alan zikir, murakabe ve sohbet gibi uygulamalar, bireyin içsel farkındalığını artırmakta, duygusal dengesini sağlamlaştırmakta ve benlik dönüşümünü desteklemektedir. Bu süreç, bireyin yalnızca semptom düzeyinde değil, daha derin bir varoluşsal düzlemde iyileşmesini mümkün kılmaktadır.

Sonuç olarak mistisizm, bireyin ruhsal sağlığı üzerinde anlam üretimi, duygusal denge, stresle başa çıkma ve benlik bütünlüğünü sağlama gibi çok boyutlu etkiler meydana getirmektedir. Bu yönüyle mistik deneyim, modern psikolojinin ele aldığı ruh sağlığı kavramını tamamlayan ve onu daha bütüncül bir perspektife taşıyan önemli bir alan olarak değerlendirilebilir.



Şekil 1. Beynin Yapısal Dönüşüm Aşamaları: Düzenli Mistik Uygulamalar Sonucu Gelişen Bilişsel Kontrol ve Artan Psikolojik Direnç Modeli.

Mistisizmden Etkilenen Modern Terapiler

Mistisizmin ruhsal sağlık üzerindeki etkilerinin yalnızca teorik düzeyde kalmadığı, modern psikoterapi yaklaşımlarında da çeşitli biçimlerde yer bulduğu görülmektedir. Günümüzde kullanılan birçok terapi yöntemi doğrudan ya da dolaylı olarak mistik ve spiritüel geleneklerden beslenen uygulamalar içermektedir. Bu yaklaşımların temelinde, bireyin içsel deneyimlerine yönelmesi, düşünce ve duygularını yargılamadan gözlemlemesi ve kabul etmesi yer almaktadır. Bu bağlamda en dikkat çekici örneklerden biri mindfulness yani bilinçli farkındalık temelli terapilerdir. Mindfulness, bireyin içinde bulunduğu ana odaklanmasını ve yaşadığı deneyimleri yargılamadan fark etmesini amaçlamaktadır. Bu yaklaşımın kökenleri incelendiğinde özellikle Doğu mistik geleneklerinde yer alan meditasyon pratikleriyle önemli ölçüde benzerlik taşıdığı görülmektedir. Günümüzde mindfulness

temelli müdahaleler, stres, depresyon ve kaygı bozukluklarının tedavisinde yaygın olarak kullanılmakta ve bireyin duygusal düzenleme kapasitesini artırmaktadır.

Bunun yanı sıra şefkat odaklı terapi (Compassion-Focused Therapy) bireyin kendine karşı daha anlayışlı ve kabul edici bir tutum geliştirmesini hedeflemektedir. Bu yaklaşım, özellikle Budist mistik geleneklerde yer alan şefkat ve merhamet pratiklerinden etkilenmiştir. Araştırmalar, bu terapinin öz eleştiri, utanç ve travma sonrası stres gibi durumlar üzerinde olumlu etkiler oluşturduğunu göstermektedir. Ayrıca transpersonal psikoloji, insanın yalnızca zihinsel süreçlerini değil, aynı zamanda spiritüel deneyimlerini de psikolojik incelemenin bir parçası olarak ele almaktadır. Bu yaklaşım, mistik deneyimi insanın gelişim sürecinde önemli bir unsur olarak kabul etmekte ve bireyin kendini aşma (self-transcendence) deneyimlerini anlamaya çalışmaktadır.

Bu örnekler birlikte değerlendirildiğinde, modern psikolojinin geliştirdiği birçok yöntemin mistik geleneklerde uzun süredir var olan pratiklerle örtüştüğü görülmektedir. Dolayısıyla mistisizm, yalnızca tarihsel ya da dinî bir olgu olarak değil, aynı zamanda günümüz psikoterapi yaklaşımlarını besleyen önemli bir kaynak olarak da değerlendirilebilir. Bu durum, mistik deneyimin modern psikolojide yeniden yorumlanarak terapötik bir araç hâline getirildiğini göstermektedir.

Mistisizm ve Nörobilim

Son yıllarda nörobilim alanında yapılan çalışmalar, mistik ve meditasyon temelli deneyimlerin beyin üzerinde ölçülebilir etkiler oluşturduğunu göstermektedir.[31] Özellikle meditasyon ve dua gibi pratiklerin, stresle ilişkili beyin bölgelerinde aktiviteyi azalttığı ve dikkat ile farkındalıkla ilişkili alanları güçlendirdiği tespit edilmiştir. Bu bulgular, mistik deneyimlerin yalnızca öznel yaşantılar olmadığını, aynı zamanda biyolojik ve nörolojik temellere de sahip olabileceğini ortaya koymaktadır. Dolayısıyla mistisizm, bireyin ruhsal sağlığı üzerinde etkili olan çok boyutlu bir süreç olarak değerlendirilebilir.

[31] Andrew Newberg, How God Changes Your Brain (New York, 2009).



Şekil 2. Mistik Pratiklerin Nörolojik Etkileri: Amigdala Hiperaktivitesinin Azalması ve Prefrontal Korteks Regülasyonu.

Meditasyonla birlikte beynin stres merkezi daha az aktif hale gelirken, dikkat ve kontrolle ilgili bölgeler daha aktif hale geliyor. Yani bu pratikler sadece insanı iyi hissettirmiyor, beynin çalışma şeklini gerçekten değiştiriyor.[32]

Mistik Geleneklerde Ruhsal İyileşme

Mistik geleneklerin ruhsal iyileşmeye olan katkıları yalnızca teorik düzeyde değil tarihsel şahsiyetlerin yaşadığı dönüşüm süreçleri üzerinden de somut bir biçimde gözlemlenebilmektedir. Bu örnekler, bireyin yaşadığı krizlerin mistik deneyim aracılığıyla nasıl anlamlı bir dönüşüme evrilebildiğini ortaya koymaktadır. Bu bağlamda en dikkat çekici örneklerden biri Mevlânâ Celâleddîn-i Rûmî'dir.[33] Rûmî, hayatının erken dönemlerinde daha çok zahirî ilimlerle meşgul olan bir âlim iken, Şems-i Tebrizî ile karşılaşmasının ardından derin bir içsel sarsıntı yaşamıştır. Bu karşılaşma, onun mevcut kimliğini sorgulamasına ve yoğun bir duygusal dönüşüm sürecine girmesine neden olmuştur. Şems'in aniden ortadan kaybolması ise Rûmî'de büyük bir ayrılık ve acı deneyimi oluşturmuştur. Ancak bu acı, zamanla ilahî aşka ve mistik bir idrake dönüşmüş, Rûmî bu süreci şiir ve sema aracılığıyla ifade etmiştir. Bu örnek, mistik deneyimin bireyin yaşadığı duygusal kırılmaları yok etmekten ziyade, onları daha derin bir anlam düzeyine taşıyarak dönüştürdüğünü göstermektedir.

Benzer bir dönüşüm süreci, Teresa of Ávila'nın hayatında da gözlemlenmektedir.[34] Teresa, gençlik yıllarında uzun süreli hastalıklar ve yoğun psikolojik sıkıntılar yaşamış, bu süreçte bedensel zayıflık ve

[32] Ertuğrul Eşel, Dinî ve Mistik Deneyimlerin Muhtemel Bilişsel ve Nörobiyolojik Düzenekleri, Klinik Psikofarmakoloji Bülteni, Cilt: 19, 2009.

[33] Bkz. Mevlânâ Celâleddîn-i Rûmî, Mesnevî (İstanbul, 1991).

[34] Teresa of Ávila, The Interior Castle (New York, 1961).

içsel dağınıklık ile mücadele etmiştir. Ancak zamanla içsel dua (contemplative prayer), inziva ve tefekkür pratiklerine yönelmiş ve bu süreçte derin mistik deneyimler yaşamıştır. Teresa'nın kendi ifadelerine göre bu deneyimler, onun içsel parçalanmışlığını ortadan kaldırmış ve yerini derin bir huzur ve bütünlük hâline bırakmıştır. Onun "İçsel Şato" (Interior Castle) adlı eseri, insan ruhunun katman katman dönüşümünü anlatması bakımından dikkat çekicidir. Bu örnek, mistik pratiklerin psikolojik dayanıklılığı artırarak bireyin içsel bütünlüğünü yeniden inşa edebileceğini göstermektedir.

Modern psikoloji açısından değerlendirildiğinde, Carl Jung'un yaşadığı kişisel kriz de dikkat çekici bir örnek sunmaktadır.[35] Jung, Freud ile yollarını ayırdıktan sonra ciddi bir içsel bunalım sürecine girmiş ve bu dönemi "ruhsal bir çözülme" olarak tanımlamıştır. Ancak bu süreçte ortaya çıkan yoğun imgeler, rüyalar ve sembollerle bilinçli bir şekilde yüzleşmiş ve bunları anlamlandırmaya çalışmıştır. Bu deneyim, onun psikolojide "bireyleşme" (individuation) kavramını geliştirmesine zemin hazırlamıştır. Jung'un yaşadığı bu süreç mistik deneyime benzer bir biçimde bireyin içsel krizlerini bir dönüşüm ve bütünleşme sürecine dönüştürebileceğini göstermektedir.

Bu tarihsel örnekler, modern araştırmalarla da desteklenmektedir. Kenneth I. Pargament'ın dinî başa çıkma üzerine yaptığı çalışmalar, bireylerin spiritüel kaynakları kullanarak stres ve travma ile daha sağlıklı başa çıkabildiğini ortaya koymaktadır. Benzer şekilde Andrew Newberg'in çalışmaları, meditasyon ve dua gibi pratiklerin beyinde huzur ve denge ile ilişkili bölgeleri aktive ettiğini göstermektedir. Tüm bu örnekler birlikte değerlendirildiğinde, mistik deneyimin bireyin yaşadığı krizleri ortadan kaldırmaktan ziyade, bu krizleri anlamlı bir dönüşüm sürecine dönüştürdüğü görülmektedir. Bu yönüyle mistik gelenekler, ruhsal iyileşmeyi yalnızca semptomların giderilmesi olarak değil, bireyin varoluşsal düzeyde yeniden yapılanması olarak ele almaktadır.

Mistik deneyimin modern dönemde bireysel dönüşüm üzerindeki etkisine dair dikkat çekici örneklerden biri de Ayşe Şasa'dır.[36] Türk sinemasının önemli senaristlerinden biri olan Şasa, genç yaşlarda büyük bir entelektüel birikime ve üretkenliğe sahip olmasına rağmen, hayatının ilerleyen dönemlerinde derin psikolojik krizler yaşamıştır. Bu süreçte yoğun bir içsel parçalanma, yalnızlık ve anlam arayışı içinde olduğu bilinmektedir. Şasa'nın kendi ifadelerine göre bu dönem, onun için yalnızca bir rahatsızlık süreci değil aynı zamanda varoluşsal bir kırılma noktası olmuştur. Ancak bu kriz, onu tasavvufî düşünce ile tanıştıran bir sürecin de başlangıcını oluşturmuştur. Tasavvufla kurduğu ilişki, Şasa'nın yaşadığı dağınıklığı anlamlandırmasına ve içsel dünyasını yeniden inşa etmesine imkân tanımıştır. Bu süreçte mistik düşünce, onun için yalnızca teorik bir bilgi alanı değil, doğrudan yaşanan ve dönüştürücü bir deneyim hâline gelmiştir. Yaşadığı kriz, bu deneyim aracılığıyla bir çöküş olmaktan çıkarak bir dönüşüm sürecine evrilmiş; bireysel parçalanma yerini daha bütüncül bir benlik algısına bırakmıştır. Ayşe Şasa örneği, mistisizmin yalnızca tarihsel şahsiyetlere özgü bir olgu olmadığını, modern bireyin yaşadığı psikolojik krizleri anlamlandırma ve dönüştürme sürecinde de etkili bir rol oynayabileceğini açıkça ortaya koymaktadır.

Mistisizm, modern dünyada yeniden anlam kazanan bir deneyim alanı olarak, bireyin yalnızca dinî değil, aynı zamanda psikolojik ve varoluşsal ihtiyaçlarına da cevap veren bir yapı sunmaktadır. Bu bağlamda mistik deneyim, bireyin yaşadığı krizleri ortadan kaldırmaktan ziyade, onları anlamlı bir

[35] Carl Jung, The Archetypes (Princeton, 1981).

[36] Ayşe Şasa, Bir Ruh Macerası (İstanbul, 2012).

dönüşüm sürecine dönüştürmektedir. Gerek tarihsel örnekler gerekse modern araştırmalar, mistik pratiklerin bireyin ruhsal sağlığı üzerinde anlam üretimi, duygusal denge ve içsel bütünlük gibi çok boyutlu etkiler meydana getirdiğini göstermektedir. Bu durum, mistisizmin yalnızca inanç temelli bir olgu değil, aynı zamanda insanın içsel dünyasını düzenleyen bir deneyim biçimi olarak değerlendirilmesi gerektiğini ortaya koymaktadır.

Sonuç olarak mistisizm, modern psikolojinin ele aldığı ruh sağlığı kavramını tamamlayan ve onu daha derin bir boyuta taşıyan bütüncül bir perspektif sunmaktadır. Bu nedenle mistik gelenekler ile modern psikoloji arasında kurulacak bir diyalog, insanın hem zihinsel hem de varoluşsal boyutlarını birlikte ele alan daha kapsamlı bir anlayışın gelişmesine katkı sağlayabilir.

Mistik Geleneklerde Ruhsal İyileşme ve Tasavvuf Örneği

Mistik geleneklerde ruhsal iyileşme, bireyin içsel dengesini yeniden kurması ve zihinsel dağınıklığını azaltmasıyla ilişkilendirilmektedir. Bu süreçte kullanılan pratikler, doğrudan bireyin dikkatini düzenlemeyi, duygularını dengelemeyi ve anlam üretimini güçlendirmeyi hedeflemektedir. Örneğin meditasyon ve tefekkür gibi uygulamalar, bireyin zihinsel akışını yavaşlatarak sürekli düşünme ve kaygı üretme eğilimini azaltmaktadır. Bu süreçte kişi, düşüncelerini dışarıdan gözlemleyebilmekte ve bu sayede duygusal tepkilerini daha kontrollü bir şekilde yönetebilmektedir. Bu durum, modern psikolojide "mindfulness" olarak adlandırılan bilinçli farkındalık süreciyle örtüşmektedir.

Benzer şekilde tasavvuf geleneğinde yer alan bazı pratikler, ruhsal iyileşme sürecini somut bir biçimde desteklemektedir. Bu bağlamda İmam Gazâlî'nin sistemleştirdiği yaklaşımda[37] bireyin iç dünyasında ortaya çıkan dengesizliklerin belirli yöntemlerle giderilebileceği ifade edilmektedir. Örneğin zikir uygulaması, belirli kelime veya ifadelerin tekrar edilmesi yoluyla zihinsel dağınıklığı azaltmakta ve bireyin dikkatini tek bir noktada toplamasını sağlamaktadır. Bu durum, kaygı ve stresin azalmasına katkı sunmakta ve bireyde içsel bir sakinlik oluşturmaktadır. Murakabe olarak adlandırılan içsel gözlem pratiği ise bireyin kendi düşünce ve duygularını fark etmesini sağlayarak öz farkındalığını artırmaktadır. Bu süreçte kişi, otomatik tepkiler yerine daha bilinçli bir tutum geliştirebilmekte ve içsel çatışmalarını daha sağlıklı bir şekilde yönetebilmektedir. Sohbet ve rehberlik süreci de tasavvufî gelenekte önemli bir yer tutmaktadır. Bu uygulama, bireyin deneyimli bir rehber eşliğinde kendini ifade etmesine ve yönlendirilmesine imkân tanımakta, bu yönüyle modern psikolojideki terapötik ilişkiye benzer bir işlev görmektedir. Bu örnekler, mistik geleneklerde kullanılan pratiklerin yalnızca teorik değil, aynı zamanda doğrudan bireyin ruhsal durumunu etkileyen somut uygulamalar olduğunu göstermektedir. Dolayısıyla mistisizm, bireyin ruhsal iyileşmesini destekleyen deneyimsel ve uygulanabilir bir süreç olarak değerlendirilebilir.

Mistik geleneklerde ortaya konulan ruhsal iyileşme yöntemlerinin, modern psikoloji yaklaşımlarıyla çeşitli açılardan benzerlik gösterdiği dikkat çekmektedir. Nitekim bazı araştırmacılar, tasavvufî pratiklerin bireyin zihinsel ve duygusal süreçlerini düzenleme bakımından çağdaş psikoterapi teknikleriyle örtüştüğünü ifade etmektedir.

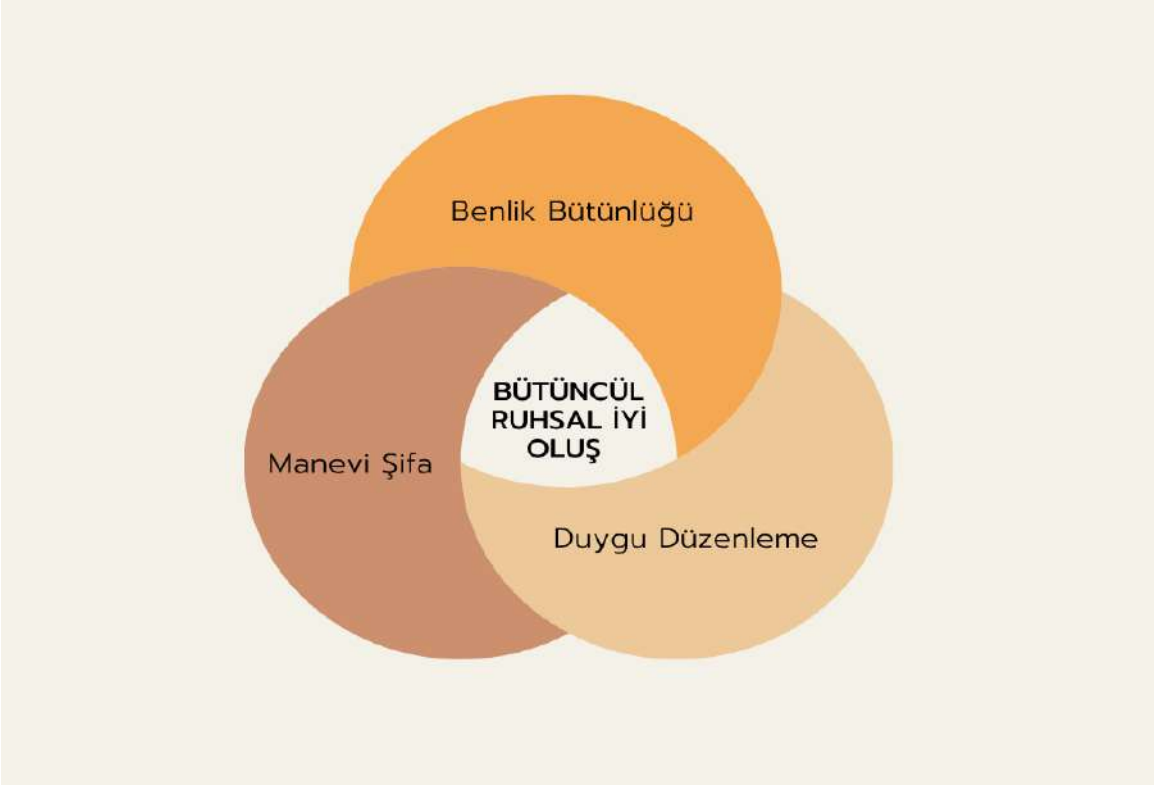
Bu bağlamda tasavvuf ile modern psikoloji arasındaki benzerlikler şu şekilde özetlenebilir:

[37] İmam Gazali, İhyâʾü ʿUlûmi'd-Dîn (İstanbul, 2004).

Tasavvuf	Modern psikoloji
Zikir	Meditasyon
Murakabe	Mindfulness
Nefis terbiyesi	Davranış değişimi
Sohbet	Terapötik ilişki

Bu karşılaştırma, tasavvufî pratiklerin yalnızca dinî bir bağlamda değil, aynı zamanda bireyin psikolojik süreçlerini düzenleyen işlevsel yöntemler içerdiğini göstermektedir. Özellikle zikir ve meditasyonun dikkat ve odaklanmayı artırması, murakabe ile mindfulness uygulamalarının öz farkındalık geliştirmesi ve sohbet ile terapötik ilişkinin bireyin kendini ifade etmesine imkân tanıması, bu benzerliğin somut örnekleri olarak değerlendirilebilir.

Dolayısıyla tasavvuf ile modern psikoloji arasında kurulan bu paralellik, mistik deneyimin yalnızca tarihsel bir olgu olmadığını, aynı zamanda günümüz insanının ruhsal ihtiyaçlarına da karşılık verebilecek bir potansiyele sahip olduğunu ortaya koymaktadır. Aslında gördüğümüz şey şu, isimler farklı ama süreçler çok benzer. Modern psikolojinin yöntemleri ile mistik geleneklerin pratikleri arasında düşündüğümüzden çok daha güçlü bir ortak zemin bulunmaktadır. Tasavvuf yalnızca bir mistik deneyim öğretisi değildir; aynı zamanda insanın iç dünyasını arındırmayı amaçlayan bir ruhsal iyileşme modelidir. Modern psikoloji zihnin sağlığını incelerken, mistik gelenekler insanın içsel bütünlüğünü hedefler. Bu iki alanın birleşmesi insanı daha bütüncül anlamamıza yardımcı olabilir. Bu nedenle modern psikoloji ile tasavvuf arasında diyalog kurulabilecek önemli bir alan bulunmaktadır.



Şekil 3. Tasavvuf Pratikleri ve Modern Psikoloji Kavramlarının Bütüncül Ruh Sağlığı Üzerindeki Kesişimi.

SONUÇ

Bu çalışmada mistisizm ile ruhsal sağlık arasındaki ilişki, farklı boyutlarıyla ele alınmıştır. Yapılan değerlendirmeler, mistisizmin yalnızca tarihsel ya da dinî bir olgu olmadığını aynı zamanda modern psikolojinin de giderek artan bir ilgiyle yaklaştığı bir deneyim alanı olduğunu göstermektedir. Özellikle William James'in dinî tecrübeyi bireysel ve doğrudan yaşanan bir deneyim olarak ele alması, bu alandaki modern yaklaşımlar için önemli bir teorik zemin oluşturmuştur.

Mistik ve spiritüel pratiklerin bireyin ruhsal sağlığı üzerindeki etkileri incelendiğinde, bu uygulamaların stresin azaltılması, duygusal denge sağlanması ve anlam üretimi gibi alanlarda olumlu katkılar sunduğu görülmektedir. Meditasyon, mindfulness, zikir ve benzeri uygulamalar, bireyin içsel farkındalığını artırarak psikolojik dayanıklılığını güçlendirmekte ve ruhsal iyilik hâline katkı sağlamaktadır. Bu durum, mistik deneyimin yalnızca öznel bir yaşantı olmadığını, aynı zamanda psikolojik süreçlerle doğrudan ilişkili olduğunu ortaya koymaktadır.

Ayrıca modern psikoloji ile mistik gelenekler arasında dikkat çekici benzerlikler bulunmaktadır. Özellikle farkındalık temelli yaklaşımlar, şefkat odaklı terapiler ve transpersonal psikoloji gibi alanlar, mistik düşüncenin bazı temel unsurlarını yeniden yorumlayarak psikoterapi süreçlerine dâhil etmektedir. Bu bağlamda mistisizm, modern psikolojinin yöntemsel ve kuramsal gelişimine katkı sunan önemli bir referans noktası olarak değerlendirilebilir.

Sonuç olarak mistisizm, bireyin ruhsal sağlığını destekleyen, içsel dönüşümü teşvik eden ve varoluşsal anlam arayışına cevap veren bütüncül bir yaklaşım sunmaktadır. Bu nedenle mistik gelenekler ile modern psikoloji arasında kurulacak disiplinlerarası bir diyalog, insanın hem zihinsel hem de varoluşsal boyutlarını birlikte ele alan daha kapsamlı bir anlayışın gelişmesine katkı sağlayabilir. Bu çerçevede mistisizm, insanın yalnızca iyileşmesini değil aynı zamanda kendini anlamlandırmasını mümkün kılan bir deneyim alanı olarak değerlendirilebilir.

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KENT MEYDANLARINDAKİ DİJİTAL DÖNÜŞÜM VE KULLANICI ALGISI ÜZERİNE NİTEL BİR ARAŞTIRMA

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Özet

Kent meydanları, tarihsel süreçte ticari, politik ve sosyo-kültürel alanların kesişme noktası olarak işlev görmüştür. Antik çağlardan bu yana kolektif belleğin ve kamusal temsilin inşa edildiği bu alanlar, toplumun ortak kullanım pratiklerini şekillendiren temel kentsel mekânlardır. Ancak, son dönemdeki teknolojik eklemlenme biçimleri, bu geleneksel rollerin köklü bir dönüşümüne ve yeniden tanımlanmasına yol açmıştır. Akıllı telefonların yaygın kullanımı ve sosyal medya platformlarının gündelik yaşama entegrasyonu ile birlikte bu alanlar, yalnızca fiziksel etkileşim mekânları olmaktan çıkarak dijital ağlarda anlık olarak yeniden üretilen "hibrit sahnelere" dönüşmektedir. Bu süreçte fiziksel mekân, yalnızca mekâna özgü bir deneyim nesnesi olmanın ötesine geçerek dijital temsillerin ve eş zamanlı bilgi akışlarının sürekli olarak yeniden üretildiği dinamik bir arayüz bileşeni haline gelmiştir. Son otuz yılı kapsayan ve kentsel kamusal alanlarla ilgili literatürün sistematik bir taramasına dayanan bu çalışma, meydanların geçirdiği dönüşümü ve kullanıcı algısının ekran dolayımlı bir arayüz düzleminde yeniden kurgulanma sürecini incelemektedir. Bulgular, özellikle 2020 sonrasında kullanıcı memnuniyetinin yalnızca erişilebilirlik ve sosyal etkileşim gibi fiziksel parametreler üzerinden değil, fotoğraflanabilirlik, estetik tutarlılık ve paylaşım değeri gibi dijital görünürlük kriterleri üzerinden de belirlendiğini ortaya koymaktadır. Bu doğrultuda, güncel tasarım

yaklaşımları kent meydanlarını salt fiziksel mekânlar olarak değil dijital temsil katmanlarıyla bütünleşmiş etkileşimli arayüz düzlemleri olarak yeniden konumlandırmaktadır. Bu çalışma, günümüz kent meydanlarının mevcut tasarım parametrelerinin yanı sıra birer görsel üretim platformu olarak da ele alınması gerektiğini savunmaktadır. Bu bağlamda araştırma, fiziksel mekân ile dijital temsili aynı anda ele alan ve katmanlı mekân programlaması ilkesine dayanan bütüncül bir tasarım yaklaşımını, yenilikçi bir müdahale stratejisi olarak önermektedir.

Anahtar Kelimeler: Kentsel kamusal mekân, kent meydanı, kamusal mekân algısı, dijital dönüşüm, hibrit mekân.

A QUALITATIVE STUDY ON DIGITAL TRANSFORMATION AND USER PERCEPTION IN URBAN SQUARES

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Abstract

Historically, urban squares have served as the intersection of commercial, political, and socio-cultural spheres. These spaces, where collective memory and public representation have been constructed since antiquity, are the essential urban spaces shaping the common usage practices of society. However, recent modes of technological augmentation have led to a radical transformation and redefinition of these traditional roles. With the widespread use of smartphones and the integration of social media platforms into daily life, these spaces are transforming from mere physical interaction spaces into "hybrid scenes" that are instantly reproduced on digital networks. In this process, physical space has transcended its role as a mere object of site-specific experience, evolving into a dynamic interface component where digital representations and simultaneous information flows are constantly reproduced. Spanning the last three decades and based on a systematic review of the literature on urban public spaces, this study examines the transformation of squares and the reconfiguration of user perception through a screen-mediated interface. The findings reveal that, particularly since 2020, user satisfaction has been determined not only by physical parameters such as accessibility and social interaction but also by digital visibility criteria such as photographability, aesthetic consistency, and shareability. Accordingly, contemporary design approaches redefine public squares not merely as physical spaces, but as interactive interface planes integrated with layers of digital representation. This study argues that contemporary urban squares should be conceived not only in terms of their existing design parameters but also as platforms for visual production. In this context, it proposes an integrated design approach that simultaneously addresses physical space and digital representation and is based on the principle of layered spatial programming as an innovative intervention strategy.

Keywords: Urban public space, urban square, perception of public space, digital transformation, hybrid space.

1. Giriş

Meydanlar, antik çağlardan bu yana kolektif belleğin ve kamusal temsilin inşa edildiği en önemli kent mekânlarıdır. Mimarlık ve şehircilik tarihinin gelişim kurgusu içerisinde, agoralardan Orta Çağ pazar meydanlarına ve modern kent planlama anlayışının kamusal alanlarına evrilen bu mekânlar, toplumsal müzakere, kültürel aktarım ve kolektif kimlik üretiminin mekânsal karşılığı olarak değerlendirilmektedir. Ancak son yirmi yılda yaşanan hızlı teknolojik dönüşüm, bu işlevlerin yeniden sorgulanmasını zorunlu kılmıştır. Bu doğrultuda dijital iletişim altyapılarının kentsel dokuya eklemlenmesi, kamusal alanın salt fiziksel bir etkileşim zemini olmaktan çıkarak, dijital ağlarla bütünleşik çok katmanlı bir deneyim sahasına evrilmesine neden olmuştur (Drucker & Gumpert, 2012). Bu dönüşümü tetikleyen en belirleyici etken, akıllı telefonların toplumsal yaşama kitlesel entegrasyonudur. Hatuka & Toch (2016), akıllı telefonun kamusal mekânda bireye taşınabilir bir özel-kişisel alan oluşturduğunu ve bu durumun kolektif deneyim pratiklerini kökten biçimlendirdiğini ileri sürmektedir. Humphreys & Hardeman (2021) ise akıllı telefon çağında kamusal alanda sosyal etkileşimin yapısal bir dönüşüme uğradığını, fiziksel ve dijital varoluşun iç içe geçtiğini vurgulamaktadır. Ayrıca, görsel paylaşım platformlarının meydan tasarımına ve kullanım pratiklerine yansıyan etkileri, mimarlık kuramında yeni bir tartışma odak noktası haline gelmiştir. Toscano (2017), bu platformların kamusal alanın sosyal algısını yeniden şekillendirdiğini ve mekânların sosyal medyada üretilen imajlarına göre değer kazandığını ya da değer yitirdiğini ortaya koymuştur.

Bu çalışma, araştırma konusu olan dönüşümü üç temel soru üzerinden irdelemektedir: (i) Kent meydanları dijitalleşme sürecinde işlevsel ve biçimsel açıdan nasıl bir dönüşüm geçirmektedir? (ii) Kullanıcı memnuniyeti ve mekân algısı, dijital görünürlük kriterleriyle nasıl bir ilişki kurmaktadır? (iii) Bu dönüşüme yanıt verecek bütüncül bir tasarım yaklaşımı nasıl geliştirilebilir? Çalışmanın özgünlüğü, sistematik literatür taramasından elde edilen kuramsal verilerin tasarım odaklı somut bir müdahale stratejisiyle sentezlenmesinden kaynaklanmaktadır.

2. Kavramsal Çerçeve

2.1. Mekânsal Parametrelerin Dönüşümü

Kamusal mekânın tarihsel işlevi, kullanıcıların fiziksel olarak aynı düzlemde bulunmasını esas alan ve mekâna bağlı eylemlerle şekillenen geleneksel bir paradigmaya dayanmaktaydı. Bu paradigmanın temel parametreleri; fiziksel toplanma ve müzakere işlevi, erişilebilirlik ve

konfor merkezli başarı ölçütleri, kurumsal ve yukarıdan aşağıya gözetim biçimleri ile sabit mimari sınırlardı. Dijitalleşme süreci ise bu parametrelerin tamamını dönüştürmüş ve yeni bir paradigmanın doğmasına zemin hazırlamıştır. Söz konusu dönüşüm, yalnızca teknolojik bir eklemlenme olarak değil, kamusal mekânın işlev, sınır, gözetim ve başarı ölçütleri gibi kurucu kategorilerinin tamamının yeniden tanımlanması olarak anlaşılmalıdır (Tablo 1).

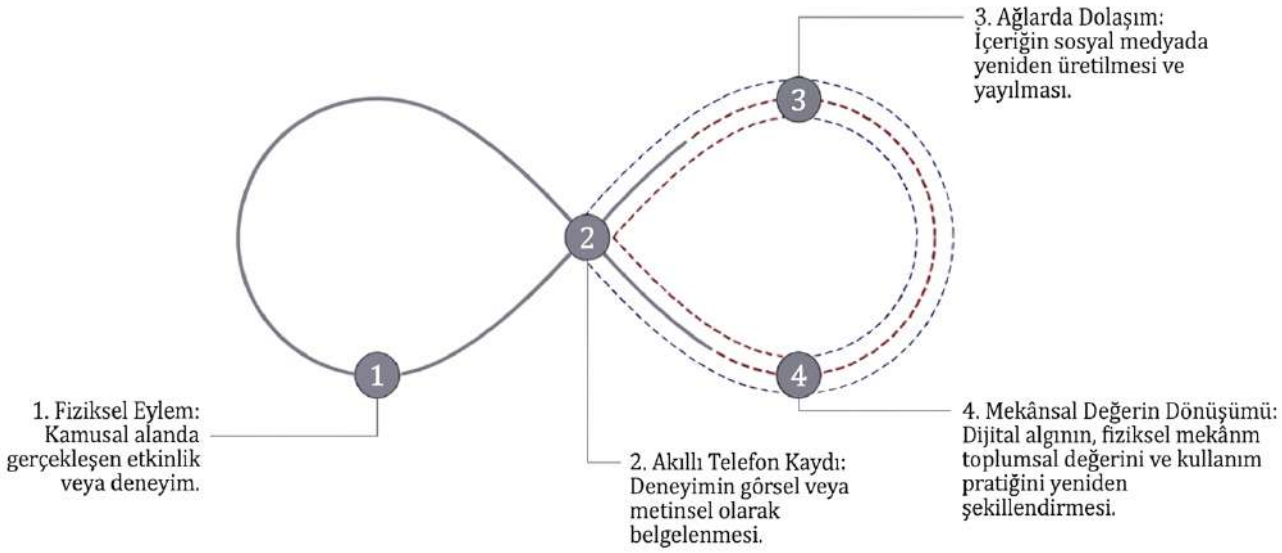
Tablo 1. *Geleneksel ve Hibrit Meydan Paradigmalarının Karşılaştırması*

Parametre	Geleneksel Meydan Paradigması	Hibrit Meydan Paradigması (Dijital Eklemlenme)
Temel İşlev	**Fiziksel Toplanma & Müzakere:** Yüz yüze etkileşim ve rasyonel-eleştirel iletişim odaklıdır (Habermas, 1991; Arendt, 1958).	**Eş Zamanlı Deneyim & Temsil:** Fiziksel eylemin dijital ağlarda bir performans sahnesine dönüşmesi (Zimmerman vd., 2014).
Başarı Ölçütleri	**Fiziksel Konfor & Erişilebilirlik:** Ergonomi, iklimlendirme ve mekânsal okunabilirlik ön plandadır (Lynch, 1960; Whyte, 1980).	**Fotoğraflanabilirlik & Paylaşım Değeri:** Dijital görünürlük potansiyeli ve estetik temsil değeri (Toscano, 2017).
Gözetim Rejimi	**Kurumsal & Merkezi:** Yukarıdan aşağıya denetim ve disipliner gözetim (Foucault, 1977; Norris & Armstrong, 1999).	**Yanal (Yatay) Gözetim:** Bireylerin birbirini enformel biçimde gözlemlediği, kayıt altına aldığı ve dijital platformlarda görünür kıldığı yatay bir izleme pratiği (Jiow & Morales, 2015).
Mekânsal Sınırlar	**Sabit & Mimari:** Fiziksel çeperler, yapılar ve tanımlı peyzaj öğeleriyle sınırlıdır (Madanipour, 1996).	**Akışkan & Taşınabilir:** Akıllı telefonların yarattığı "taşınabilir özel-kişisel alanlar" (Hatuka & Toch, 2016).
Kullanıcı Algısı	**Bedensel Mevcudiyet:** Mekânla kurulan birincil, fiziksel ve dokunsal ilişki (Sennett, 1977).	**Asimetrik Görünürlük:** Dijital öz-sunum ve algoritmik görünürlük üzerinden kurulan ilişki (Sharon & Koops, 2021; Timan & Albrechtslund, 2018).

Hibrit meydan paradigmasında temel işlev eş zamanlı fiziksel deneyim ve dijital temsile dönüşmüş; başarı ölçütleri fotoğraflanabilirlik (photographability) ve paylaşım değeri gibi dijital görünürlük kriterleriyle genişlemiştir. Gözetim mekanizması kurumsal ve merkezi yapısından sıyrılarak bireylerin birbirini enformel biçimde gözlemlediği yanal gözetime (lateral surveillance) ve asimetrik görünürlüğe dönüşmüştür. Mekânın sınırları ise fiziksel sınırlardan akıllı telefonlarla birlikte taşınabilir özel-kişisel alanlara evrilmiştir.

2.2. Dijital Eklemlenme ve Hibrit Mekân

Güncel literatürde kamusal mekân, yalnızca fiziksel bir alan olarak değil, dijital katmanlarla iç içe geçmiş bütüncül bir yapı olarak ele alınmaktadır. Bu doğrultuda Zimmerman vd. (2014), kenti dijital verilerin sürekli dolaşım halinde olduğu ve mekânsal deneyimi doğrudan etkilediği hibrit bir sistem olarak tanımlamaktadır. Yazarların ortaya koyduğu "dijital yansıma" (digital reverberation) kavramı, fiziksel alanda gerçekleşen bir eylemin dijital ağlara aktarılmasını ve oradaki etkileşimin tekrar fiziksel mekânın değerini değiştirmesini açıklayan döngüsel bir süreci ifade etmektedir (Şekil 1).



Şekil 1. *Dijital Yansıma (Digital Reverberation) Döngüsü (Zimmerman vd., 2014 temel alınarak yazar tarafından oluşturulmuştur)*

Mekânın dijitalleşmesi, sosyal pratiklerin ve toplumsal anlamların yeniden kurgulanmasına yol açmıştır. Riether (2011), dijital medyanın kentsel yaşamın ayrılmaz bir parçası olduğunu savunurken; Abdel-Aziz vd. (2016), teknolojinin geleneksel meydanların işlevlerini sanal düzleme genişleterek yeni bir kamusal mekân türü ortaya çıkardığını belirtmiştir. Di Marino vd. (2023) ise "hibrit kent" kavramsallaştırmasıyla fiziksel ve dijital mekânın birbirinin yerine geçmediğini, aksine birbiriyle iç içe geçmiş katmanlar oluşturduğunu savunmaktadır. Bu yaklaşıma göre meydanlar, deneyimin yalnızca bedensel mevcudiyete değil, aynı zamanda dijital bağlantı durumuna ve paylaşım pratiklerine de eklemlendiği çok katmanlı alanlara dönüşmektedir.

3. Yöntem

Bu çalışma, son otuz yılda kentsel kamusal alanların dijitalleşme sürecini inceleyen literatürü kapsamaktadır. Araştırma dahilinde Web of Science veri tabanı üzerinden 'public space' (kamusal alan), 'smartphone' (akıllı telefon), 'social media' (sosyal medya), 'digital transformation' (dijital dönüşüm) ve 'hybrid space' (hibrit mekân) gibi temel anahtar kelimelerle kapsamlı bir tarama gerçekleştirilmiştir. İnceleme sürecine 120'yi aşkın yayın dahil edilerek konuyla doğrudan ilgili, akademik niteliği yüksek olan çalışmalar belirlenmiştir. Bu yayınlar kuramsal yaklaşımları, yöntemsel tercihleri, incelenen mekân türleri ve temel bulgular açısından gruplandırılarak analiz edilmiştir. Ayrıca, alanın yapısal eğilimlerini görselleştirmek ve literatürdeki ağ ilişkilerini ortaya koymak amacıyla sistematik tarama süreci bibliyometrik analizlerle desteklenmiştir.

4. Bulgular

4.1. Bibliyometrik Bulgular

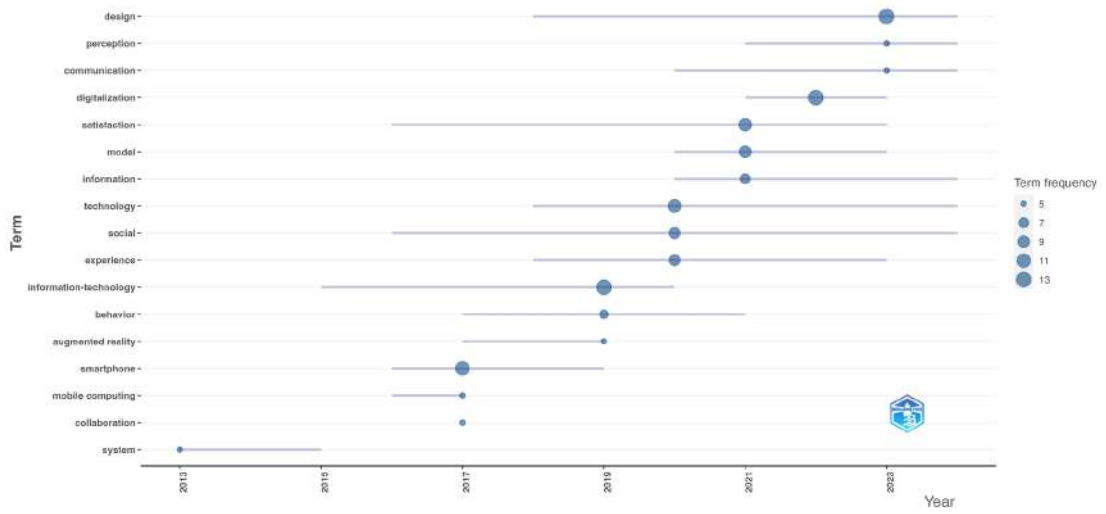
Araştırma kapsamında gerçekleştirilen kelime bulutu analizi, incelenen literatürün kavramsal ağırlık merkezini ve akademik ilginin yoğunlaştığı temel odak noktalarını açık bir biçimde ortaya koymaktadır (Şekil 2). En baskın kavram olarak 'information-technology' (bilgi teknolojisi) öne çıkmakta, bunu 'digitalization' (dijitalleşme), 'design' (tasarım) ve 'smartphone' (akıllı telefon) izlemektedir. Orta yoğunluklu kavramlar arasında ise 'satisfaction' (memnuniyet), 'public space' (kamusal alan), 'social' (sosyal), 'experience' (deneyim), 'model' (model), 'behavior' (davranış) ve 'augmented reality' (artırılmış gerçeklik) yer almaktadır. Bu dağılım; alanın (i) teknoloji ve dijitalleşme, (ii) mekân ve kentsel deneyim, (iii) kullanıcı davranışı ve memnuniyeti olmak üzere üç temel söylemsel eksen etrafında örgütlendiğini göstermektedir. Kamusal alanın bu üç eksenin kesişim noktasında konumlanması, konunun disiplinlerarası niteliğini hem bir kavramsal potansiyel hem de metodolojik bir ikilem olarak sunan karmaşık bir yapıya işaret etmektedir.



Şekil 2. *Kelime Bulutu Analizi: Kamusal Alan ve Dijitalleşme Literatürünün Kavramsal Ağırlık Haritası*

Literatürün zamansal gelişimi incelendiğinde; kavramsal odağın teknik altyapıdan kullanıcı deneyimine doğru evrildiği görülmektedir (Şekil 3). 2013 yılından itibaren 'system' (sistem) kavramı tartışmaların zeminini oluşturmaya başlamış, 2016–2017 döneminde ise 'smartphone' (akıllı telefon), 'mobile computing' (mobil bilişim) ve 'collaboration' (iş birliği) temaları literatürde ağırlık kazanmıştır. 2019 yılına gelindiğinde, 'information-technology' (bilgi teknolojisi) ve 'social' (sosyal) kavramlarının yanı sıra 'behavior' (davranış) ve 'augmented reality' (artırılmış gerçeklik) gibi daha spesifik etkileşim biçimleri baskın hale gelmiştir.

Araştırma gündemindeki en kritik kırılma 2021–2023 döneminde yaşanmıştır. Bu süreçte 'digitalization' (dijitalleşme) ve 'design' (tasarım) kavramları en yüksek kullanım frekansına ulaşırken, 'satisfaction' (memnuniyet), 'perception' (algı) ve 'communication' (iletişim) temaları da ivme kazanmıştır. Bu örüntü, pandemi sonrası dönemde akademik ilginin dijitalleşen mekânlara yönelik keskin bir artış gösterdiğini ve odağın 'user experience' (kullanıcı deneyimi) ile memnuniyet analizlerine kaydığını ortaya koymaktadır. Özellikle 'design' (tasarım) kavramının 2023 yılında zirveye ulaşması, literatürün mevcut durumu betimleyen kuramsal yaklaşımlardan, çözüm üreten ve tasarım odaklı müdahale biçimlerine doğru bir paradigma değişimi içinde olduğunu işaret etmektedir.



Şekil 3. *Anahtar Kavramların Zamansal Dağılımı ve Trend Analizi (2013–2024)*

4.2. Kullanıcı Algısında Yeni Parametreler

Kelime bulutu analizinde 'satisfaction' (memnuniyet) ve 'experience' (deneyim) kavramlarının ön plana çıkması, kullanıcı deneyimi araştırmalarının kamusal mekân literatüründe merkezi bir konuma yerleştiğini göstermektedir. Bu bağlamda Toscano (2017), görsel odaklı platformların kamusal alanların sosyal algısını yeniden kurguladığını belirtmiştir. Bu durum, geleneksel parametrelere ek olarak 'photographability' (fotoğraflanabilirlik) ve 'shareability' (paylaşım değeri) gibi yeni bileşenlerin, mekân kalitesinin ve tasarım pratiklerinin ayrılmaz birer parçası haline geldiğini göstermektedir. Zhao vd. (2025) tarafından yapılan bir başka araştırma, dış mekân termal konfor değerlendirmelerinin dijital içerik üretimi pratikleriyle doğrudan ilişkili olduğunu saptamıştır. Bu bulgu, fiziksel konfor ile dijital deneyim arasındaki sınırların belirsizleştiğini ve bu iki kavramın birbirini eş zamanlı olarak dönüştüren bütünleşik bir yapıya evrildiğini ortaya koymaktadır. Benzer bir yaklaşımla Yao vd. (2025), dijital katmanların fiziksel mekâna stratejik olarak eklemlenmesinin toplumsal etkileşimi artırabileceğini ve topluluk aidiyetini pekiştirebileceğini vurgulamaktadır.

4.3. Teknolojik Altyapı ve Mekânsal Etkileri

Kamusal mekân araştırmalarındaki geleneksel yaklaşımlar, bilişim teknolojilerinin baskın hale gelmesiyle birlikte evrilmiş ve teknoloji artık mekânın hem kuramsal zeminini hem de temel araştırma odağını oluşturan ana unsura dönüşmüştür. Bu bağlamda Abdel-Aziz vd. (2016), bilgi ve iletişim teknolojilerinin dijital çağın yeni kamusal mekânını inşa etmede

belirleyici bir rol üstlendiğini savunmaktadır. Mekânsal etkileşimin teknolojik boyutu üzerine odaklanan Chang vd. (2024), paylaşımlı cihazların toplumsal kontrol süreçleri üzerindeki etkisini inceledikleri araştırmalarında, katılımcı tasarım ilkelerinin önemini vurgulamaktadır. Öte yandan Noreikis vd. (2019), artırılmış gerçeklik uygulamalarının kullanıcı ile mekân arasındaki etkileşim derinliğini artırdığını ortaya koymuştur. Ayrıca çalışma artırılmış gerçekliğin kamusal alan tasarımına entegrasyonunun yalnızca teknik bir uygulama olmadığını, mekânsal deneyimin niteliğini doğrudan dönüştüren bir boyut taşıdığını göstermektedir.

5. Tartışma: Katmanlı Mekân Programlaması

Kamusal mekânı odağına alan güncel literatürde fiziksel ve dijital boyutlar, genellikle birbirinden ayrık araştırma alanları olarak incelenmektedir. Bu teorik ayrışma, fiziksel mekân tasarımı ile dijital sistem tasarımının ortak bir metodolojik zemine taşınamamasına neden olmakta ve alanın tasarım pratiğindeki uygulama olanaklarını kısıtlamaktadır. Akıllı telefon teknolojileri ile mekânsal tasarım parametrelerinin birbirinden bağımsız ele alınması, her iki bileşeni ortak bir sistemin bütünleşik unsurları olarak kavramsallaştıracak kuramsal bir çerçevenin eksikliğini açığa çıkarmaktadır. Hibrit mekân gerçekliği, fiziksel, temsili ve etkileşimsel süreçleri bütünleşik bir yapı içinde ele alan yeni bir tasarım paradigmasının geliştirilmesini zorunlu kılmaktadır. Bu doğrultuda çalışma, mekânı hiyerarşik ve işlevsel olarak birbirini destekleyen üç düzlemde kavramsallaştıran "Katmanlı Mekân Programlaması" modelini önermektedir.

Katman 1: Fiziksel Katman

Fiziksel katman, mekânın somut, dokunulabilir ve bedensel deneyime açık temel boyutunu tanımlamaktadır. Bu katmanda erişilebilirlik ve yaya dolaşım organizasyonu, güvenlik ve aydınlatma düzeni ile oturma grupları ve ergonomik konfor, birincil tasarım parametreleri olarak öne çıkmaktadır. Lynch (1960) ve Whyte'ın (1980) kentsel kullanılabilirlik ilkeleriyle örtüşen bu parametreler, mekânsal deneyimin niteliğini doğrudan belirleyen ön koşulları oluşturmaktadır. Bununla birlikte fiziksel katmanın işlevsel kapsamı, geleneksel bir tasarım anlayışıyla sınırlı kalmamaktadır. Bu katman, aynı zamanda üst katmanların —temsil ve etkileşim— üzerine inşa edileceği yapısal ve duyusal zemini oluşturmaktadır. Bir başka deyişle, geleneksel tasarım parametreleri bu düzlemde geçerliliğini ve önceliğini korurken, fiziksel katman bütüncül sistemin taşıyıcı altyapısı olarak da işlev görmektedir. Mekânın fiziksel konfor ve çevresel kalite bağlamındaki başarısı, üst katmanların etkinliğini doğrudan koşullandırmakta ve dijital deneyimin temellendirileceği nitelikli düzlemi oluşturmaktadır.

Katman 2: Temsil Katmanı

Temsil katmanı, fiziksel mekânın dijital platformlarda yeniden üretilme, görsel olarak dolaşıma girme ve anlam kazanma potansiyelini tanımlamaktadır. Kullanıcı memnuniyetinin ve mekânsal tercih örüntülerinin giderek artan ölçüde dijital görünürlük pratikleri üzerinden şekillendiği günümüz koşullarında bu katman, üç kritik tasarım parametresi üzerine temellendirilmektedir. Bileşenlerden ilki olan *fotoğraflanabilirlik*, mekânsal öğelerin optik cihazlar için doğal çerçeveleme alanları ve hiyerarşik görsel odak noktaları oluşturacak biçimde konumlandırılmasını esas almaktadır. İkinci kriter olan *estetik tutarlılık*, mekânın fiziksel doku, yüzey ve malzeme özelliklerinin dijital ekranlardaki renk, doygunluk ve ışık algısıyla uyumlu bir bütünlük sağlayacak şekilde kurgulanmasına dayanmaktadır. Son olarak *ölçek ve oran*, mekânsal öğelerin görsel platform standartlarıyla örtüşen bir kompozisyon üretebilmesi için fiziksel boyut ilişkilerinin dijital görünürlük parametreleri gözetilerek yeniden tanımlanmasını gerektirmektedir.

Mekân kalitesi değerlendirmelerinin, yaşanan dönüşümle birlikte yalnızca fiziksel kullanılabilirlik ölçütleriyle sınırlandırılamayacağı, sosyal medya platformlarının mekânın toplumsal algısını ve çekicilik değerini doğrudan biçimlendirdiği ortaya konulmuştur (Toscano, 2017). Bu süreç, dijital görünürlük değerini kentsel tasarımın bağımsız bir parametresi olarak öne çıkarmakta ve temsil katmanını güncel tasarım pratiğinin vazgeçilmez bir unsuru olarak konumlandırmaktadır.

Katman 3: Etkileşim Katmanı

Etkileşim katmanı, mekânın kullanıcıyla dinamik, çift yönlü ve anlık bir ilişki kurmasını sağlayan teknoloji tabanlı sistem tasarımını kapsamaktadır. Bu katman, kamusal alanı pasif bir deneyim düzleminden aktif bir etkileşim arayüzüne dönüştürmeyi hedeflemektedir. Bu doğrultuda kullanıcıların aydınlatma ve su öğeleri gibi mekânsal bileşenleri anlık olarak yönetebildiği paylaşımlı arayüz kontrol sistemleri (Chang vd., 2024); konum tabanlı dijital eklemeler aracılığıyla mekânın tarihsel, kültürel ve işlevsel anlam katmanlarını zenginleştiren artırılmış gerçeklik uygulamaları (Noreikis vd., 2019) ve tüm bu bileşenlerin işlevselliğini destekleyen kesintisiz veri akışını ve mekânsal veri toplamayı sağlayan bilişim altyapısı (Osaba vd., 2018), bu katmanın birbirini tamamlayan kurucu unsurları olarak bir arada işlev görmektedir.

Bu üç katmanın bütünleşik biçimde kurgulanması, mekânsal deneyim kalitesi ile dijital temsil boyutunu eş zamanlı olarak ele alan hibrit kamusal mekânların tasarımına olanak tanımaktadır. Mekânsal kararların yalnızca fiziksel kullanılabilirlik ölçütleriyle değil, dijital temsil ve etkileşim boyutları da gözetilerek alınması, bu bütünleşik yaklaşımın temel gerekliliğini oluşturmaktadır. Katmanlı mekân programlaması, fiziksel ile dijitali ortak bir tasarım çerçevesinde bir araya getirerek kentsel meydanları hem deneyimlenen hem de eş zamanlı olarak yeniden üretilen mekânsal arayüzlere dönüştürme potansiyeli taşımaktadır.

6. Sonuç

Bu çalışmada, kent meydanlarının dijital dönüşümü ve bu dönüşümün tasarım pratiklerine yansımaları incelenmiştir. Araştırma sonuçları, kamusal mekânın dijitalleşme süreciyle birlikte salt teknik ve işlevsel bir düzlem olmanın ötesine geçtiğini, kullanıcı algısı, görsel temsil ve tasarım pratiğinin arakesitinde yeniden kurgulanan çok boyutlu ve hibrit bir olguya dönüştüğünü ortaya koymaktadır. Bu dönüşüm, kullanıcı memnuniyetinin fiziksel kullanılabilirlik parametreleriyle tam olarak sınırlandırılamayacağını, fotoğraflanabilirlik, estetik tutarlılık ve paylaşım değeri gibi dijital görünürlük kriterlerinin de mekânsal tasarım kararlarını doğrudan biçimlendiren etkenler arasına girdiğini göstermektedir.

Kamusal mekânlar, bu süreçte yalnızca bedensel varlıkla deneyimlenen fiziksel zeminler olmaktan çıkmış, dijital platformlarda eş zamanlı olarak var olan, dolaşıma giren ve yeniden anlamlandırılan hibrit yapılara evrilmiştir. Bu bağlamda çalışmanın önerdiği “Katmanlı Mekân Programlaması” modeli, fiziksel, temsil ve etkileşim katmanlarını ortak bir tasarım çerçevesinde bir araya getirerek kentsel meydanları hem deneyimlenen hem de eş zamanlı olarak yeniden üretilen mekânsal arayüzlere dönüştürme potansiyeli taşımaktadır. Bu model, yalnızca teknik bir programlama önerisi değil kamusal alanı dijital çağın gerekliliklerine göre yeniden yapılandıran, kentsel tasarım disiplinini hibrit bir düzleme taşıyan ve fiziksel ile dijitali ortak bir kavramsal düzlemde birleştiren stratejik bir tasarım yaklaşımıdır.

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GENERATIVE AI AS A DESIGN ASSISTANT IN EARLY ARCHITECTURAL DESIGN STAGE: OPPORTUNITIES AND LIMITATIONS

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Abstract

The rapid proliferation of generative artificial intelligence (GenAI) tools has established a new paradigm of practice across creative and technical disciplines. These tools also have the potential to transform the early conceptual phase, which is the complex and decision-making phase of the architectural design process. This study evaluates how these tools function as design assistants during the conceptual phase of architectural projects. In this context, applied and theoretical research published between 2016 and 2026 in the fields of architecture, architectural design process, design cognition, and conceptual design has been systematically reviewed and synthesized. The study examines in detail opportunities such as accelerated idea generation, exploration of a wide range of design alternatives, enhanced visual communication, and support for creative thinking. In addition, limitations such as context sensitivity, difficulties in BIM/CAD integration, output control issues, and concerns regarding design originality are evaluated. The findings indicate that GenAI tools significantly accelerate the early conceptual process by enabling architects to explore a wide range of design alternatives in a short period of time. In addition, it is observed that how and where these tools are positioned within the design process has impact on the architect's creative autonomy and the quality of the generated output. The study concludes that when vehicles are positioned not as autonomous producers but as collaborative design partners, they hold significant potential for enhancing the efficiency of the process. Accordingly, the study presents inferences regarding which tools should be used at which stage of the design process and under what constraints; the implications of these findings for the discipline of architecture are discussed.

Keywords: Architectural design process, Design cognition, Human-AI collaboration, Generative AI, Conceptual design.

ERKEN MİMARİ TASARIM AŞAMASINDA TASARIM YARDIMCISI OLARAK ÜRETKEN YAPAY ZEKA:

FIRSATLAR VE SINIRLILIKLAR

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Özet

Üretken yapay zeka (GenAI) araçlarının hızla yaygınlaşması, yaratıcı ve teknik disiplinlerde yeni bir çalışma biçimi ortaya koymuştur. Bu araçlar, aynı zamanda mimari tasarım sürecinin karmaşık ve yoğun karar evresi olan erken kavramsal aşamayı dönüştürme potansiyeli taşımaktadır. Bu çalışma, söz konusu araçların, mimari projelerin başlangıç evresinde tasarım asistanı olarak nasıl işlev gördüğünü değerlendirmektedir. Bu kapsamda 2016–2026 yılları arasında yayımlanan mimarlık, mimari tasarım süreci, tasarım bilişi ve kavramsal tasarım alanlarındaki uygulamalı ve kuramsal araştırmalar sistematik biçimde taranmış ve sentezlenmiştir. Araştırma, hızlandırılmış fikir üretimi, geniş tasarım seçeneği keşfi, gelişmiş görsel iletişim ve yaratıcı düşünceye destek gibi fırsatları ayrıntılı biçimde ele almaktadır. Bunların yanı sıra bağlam duyarlılığı sınırlılıkları, BIM/CAD entegrasyon güçlükleri, çıktı kontrolü sorunları, tasarım özgünlüğüne ilişkin kaygılar gibi kısıtlar da değerlendirilmektedir. Bulgular; GenAI araçlarının mimarların kısa sürede geniş tasarım alternatiflerini keşfetmesine olanak tanıyarak erken kavramsal süreci önemli ölçüde hızlandırdığını ortaya koymaktadır. Bununla birlikte, bu araçların tasarım sürecinde nerede ve nasıl konumlandırıldığının, mimarın yaratıcı özgürlüğü ve üretilen çıktının niteliği üzerinde etkili olduğu gözlemlenmiştir. Çalışma, araçların özerk bir üretici olarak değil, iş birliğine dayalı bir tasarım ortağı olarak konumlandırıldığında sürecin verimliliği adına önemli bir potansiyel taşıdığı sonucuna varmaktadır. Bu doğrultuda çalışma, hangi aracın hangi tasarım aşamasında ve hangi kısıtlar gözetilerek kullanılması gerektiğine dair çıkarımlar ortaya koymakta; bu çıkarımların mimarlık disiplini için taşıdığı sonuçlar tartışılmaktadır.

Anahtar Kelimeler: Mimari tasarım süreci, Tasarım bilişi, İnsan-YZ işbirliği, Üretken yapay zeka (GenAI), Kavramsal tasarım.

1. Giriş

Mimari tasarım süreci; keşif, kavramlaştırma, şematik tasarım, tasarım geliştirme ve belgeleme gibi birbirini izleyen ya da iç içe geçen aşamalardan oluşmaktadır (Caetano vd., 2020). Bu aşamaların belirsiz, karmaşık ve aynı zamanda üretici rol üstlenen erken kavramsal evre ise; tasarım probleminin tanımlandığı, mekânsal ve işlevsel gereksinimlerin biçimlendiği ve fikirlerin ilk kez somutlaştığı zaman dilimidir. Söz konusu evre, iyi tanımlanmış bir çözüm aramaktan çok, gereksinimler ile olası çözümlerin birlikte keşfedildiği açık uçlu bir bilişsel süreç olarak kabul görmektedir (Pena vd., 2021).

GenAI araçları bu noktada, mimarın düşünce sürecini destekleyen, fikir çeşitliliğini artıran ve görsel iletişimi kolaylaştıran yeni bir asistan rolü üstlenmektedir. Geleneksel CAD ve parametrik tasarım araçlarından farklı olarak bu araçlar, önceden tanımlanmış kurallar ya da geometrik kısıtlar olmaksızın doğal dil, eskiz veya referans görsel girdilerinden başlayarak beklenmedik ve çeşitli çıktılar üretebilmektedir. Bu kapasite, özellikle tasarım seçeneği keşfinin hem en kritik hem de en zaman yoğun olduğu erken kavramsal aşamada önemli bir potansiyel taşımaktadır. Nitekim son yıllarda mimarların bu araçları stüdyo ortamında ve profesyonel pratikte denemeye başladığına dair artan sayıda araştırma bu ilgiyi doğrulamaktadır (Jang vd., 2025; Li vd., 2025; Yiannoudes, 2025).

Bununla birlikte, araçların tasarım sürecine entegrasyonu basit bir verimlilik meselesiyle sınırlı kalmamaktadır. Mimarın yaratıcı özerkliği, disipliner kimliği ve mesleki sorumluluğu üzerindeki etkileri giderek derinleşen bir tartışmanın konusu haline gelmektedir (Hikmet ve Ozay, 2026; Yiannoudes, 2025). Yapay zekanın tasarım sürecinde özerk bir üretici mi, yoksa mimarın kapasitesini artıran bir iş birliği ortağı mı olarak konumlandırılması gerektiği sorusu; teknik bir tercih olmaktan öte, tasarım üretim biçimini ve mimarın süreçteki rolünü yeniden tanımlayan temel bir yaklaşım problemidir. Labuda'nın (2025) vurguladığı üzere, GenAI ile rekabet eden mimarın temel avantajı hız ya da üretim hacmi değil; yaratıcılık, problem kurma yeteneği ve eleştirel yargıdır. Bu çerçevede araçların nerede ve nasıl devreye girdiği, tasarım çıktısının niteliği kadar mimarın mesleki konumunu da belirlemektedir.

Bu çalışma; 2016–2026 yılları arasında yayımlanan araştırmaları tarayarak GenAI araçlarının mimari tasarımın erken kavramsal aşamasında nasıl konumlandırıldığını, ne tür fırsatlar ve kısıtlar yarattığını ve hangi koşullar altında etkili birer tasarım asistanına dönüşebildiğini değerlendirmeyi amaçlamaktadır. Bu doğrultuda mimarlık, tasarım bilişi, insan-bilgisayar etkileşimi ve üretici tasarım literatürlerine dayanan bütünleşik bir sentez

sunulmaktadır. Nicel ve nitel analizin bu bütünleşik yapısı, hem literatürün genel eğilimlerini haritalandırmayı hem de bireysel çalışmaların argümanlarını derinlemesine kavramayı olanaklı kılmaktadır.

2. Kavramsal Çerçeve

Erken kavramsal aşama, tanımlanmış bir arama uzayında çözüm aramaktan çok gereksinimlerin ve olası çözümlerin birlikte keşfedildiği bir süreçtir (Pena vd., 2021); bu niteliği, süreci diğer tasarım evrelerinden ayırmaktadır. Söz konusu belirsizlik, aynı zamanda sürecin en yaratıcı ve en değer üretici boyutunu oluşturmaktadır. Nitekim mimarlık eğitimi bağlamında yürütülen araştırmalar, erken kavramsal evredeki öğrenmenin tasarımcı kimliğini ve yaratıcılık anlayışını doğrudan biçimlendirdiğini göstermektedir (Taneri, 2021). Bu bulgu, kavramsal aşamanın yalnızca bir üretim evresi değil, aynı zamanda tasarımcı bilişinin inşa edildiği bir alan olduğuna işaret etmektedir.

Geleneksel tasarım süreçlerinde bu evre; eskizler, fiziksel maketler ve bilişsel haritalar gibi araçlarla yürütülmektedir. Parametrik tasarım ortamlarında ise çalışan mimarların tasarım kalıplarına başvuru sıklığı ve çeşitliliği, geometrik modelleme ortamlarına kıyasla anlamlı biçimde farklılaşmakta (Yu ve Gero, 2016); dijital ve fiziksel prototipleme yöntemlerinin farklı niteliklerde tasarım kararları ürettiği, iki modaliteyi birleştiren hibrit yaklaşımların ise tek başına kullanılan yöntemlere kıyasla daha zengin çıktılar sağladığı görülmektedir (Kim, 2019). Bhooshan (2017) bu ilişkiyi kavramsal düzeyde ele alarak bilişsel model, tasarım yöntemi ve bilgi işleme sürecinin birbirinden bağımsız düşünülemeyeceğini göstermektedir. Bu bakış açısından GenAI araçları, temelden farklı bir temsil mantığı getirerek erken kavramsal evreyi yeniden biçimlendirme potansiyeli taşımaktadır.

Üretici tasarım kavramı, evrimsel algoritmalar ve parametre tabanlı biçim üretimiyle başlayarak, büyük veri ve derin öğrenmenin olgunlaşmasıyla köklü bir metodolojik dönüşüm geçirmiştir (Zhuang vd., 2025). Bu algoritmaların mimari tasarıma entegrasyonu ise yalnızca üretim süreçlerini değil, performans-tasarım-öğrenme ilişkisini de dönüştürmekte; bu durum, mimarların veri yoğun ortamlardan daha etkin yararlanabilmesi için yeni pratik çerçeveler gerektirmektedir (Tamke vd., 2018). Günümüzde Üretken Çekişmeli Ağlar (GAN), Değişken Otokodlayıcılar (VAE) ve difüzyon modelleri mimari bağlamda giderek artan ilgi görmektedir. Bu modeller, yalnızca işlevsel değil aynı zamanda bilgi üretici niteliğe sahiptir. Tasarımcının kontrolü ne ölçüde elinde tuttuğu, üretilen çıktının niteliğini ve tasarımcının yaratıcı özerkliğini

doğrudan belirlemektedir. YZ tabanlı araçlarla etkin biçimde çalışmak, geleneksel CAD araçlarından farklı, kendine özgü beceriler gerektirmekte; bu "iş birliği yetkinliği", pratik bağlamda henüz yeterince tanımlanmamış bir kavram olarak devam etmektedir (Gmeiner vd., 2023).

3. Yöntem

Bu çalışma, sistematik ve tekrarlanabilir bir araştırma çerçevesi oluşturmak amacıyla birbirini izleyen dört modülden oluşan bir veri işleme mimarisi üzerine kurgulanmıştır. Veri toplama aşamasında Clarivate Web of Science veri tabanı kullanılmış; veri filtreleme aşamasında dahil etme ve dışlama ölçütleri uygulanarak 109 kaynak belirlenmiştir. Nicel analiz aşamasında R biblioshiny (Aria & Cuccurullo, 2017) paketi aracılığıyla yıllık bilimsel üretim, tematik haritalama ve anahtar kelime ilişki ağı analizleri gerçekleştirilmiştir. Nitel analiz aşamasında ise kaynakların kavramsal içeriğine inilerek fırsatlar ve kısıtlar yorumlayıcı bir yaklaşımla sentezlenmiştir.

Veri toplama sürecinde; ("generative AI" OR "ai-assisted design") AND ("architectural design" OR "design in architecture") AND ("conceptual design" OR "design process" OR "design cognition" OR "early stage" OR "concept generation") arama dizisi uygulanmıştır.

Yayın türü filtresi olarak makale, derleme makalesi ve konferans bildirisi kategorileri seçilmiştir. Zaman aralığı 2016–2026 olarak belirlenmiş olup bu dönem, derin öğrenme modellerinin tasarım uygulamalarına entegrasyonunun hız kazandığı evreye karşılık gelmektedir. Tarama sonucunda toplam 110 kaynak elde edilmiştir.

Veri filtreleme aşamasında çalışmaların kapsama alınabilmesi için makale, derleme makalesi veya konferans bildirisi türünde ve İngilizce dilinde yayımlanmış olması; mimari tasarım süreci ya da üretici yapay zeka konusunu doğrudan ele alması; kavramsal ya da erken tasarım aşamasını doğrudan veya dolaylı olarak kapsaması ölçüt olarak benimsenmiştir. Yalnızca yapısal performans optimizasyonuna odaklanan ve mimari tasarım süreciyle bağlantısı kurulamayan çalışmalar kapsam dışında tutulmuştur. Bu süreç sonucunda 1 kaynak çıkarılmış; analize 109 kaynak dahil edilmiştir.

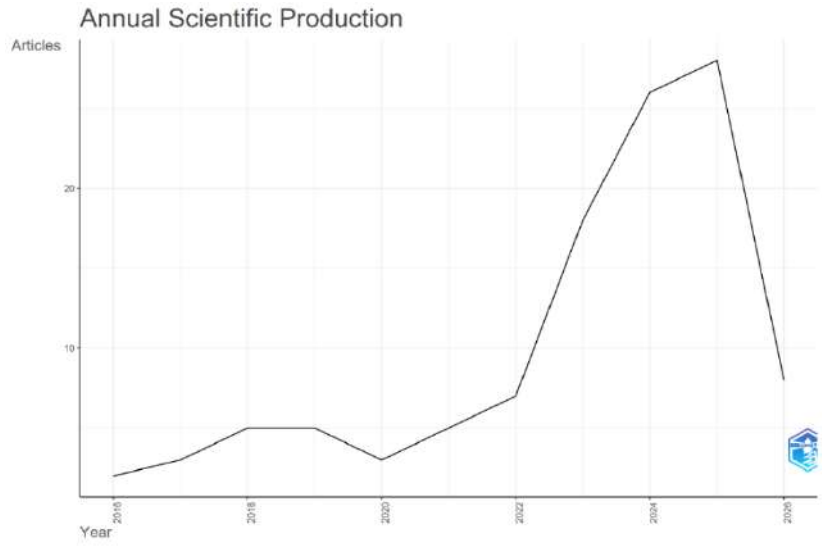
Analiz kapsamında R biblioshiny (Aria & Cuccurullo, 2017) paketi kullanılarak istatistiksel ve ağ analizleri gerçekleştirilmiştir. Yıllık bilimsel üretim, tematik haritalama, anahtar kelime ilişki ağı ve kümeleme analizi bu sürecin temel çıktılarını oluşturmaktadır. Nitel analiz

aşamasında ise kaynakların kavramsal derinliğine inilmiş; fırsatlar, kısıtlar ve insan-yapay zeka iş birliği dinamikleri yorumlayıcı bir yaklaşımla sentezlenmiştir.

4. Bulgular

4.1. Yıllık bilimsel üretim analizi

Elde edilen yayınların yıllara göre dağılımına bakıldığında, 2016–2020 döneminde yıllık yayın sayısının 2 ile 6 arasında kaldığı; 2020 sonrasında ise üretimde belirgin bir artış yaşandığı görülmektedir. 2022 yılı, ChatGPT ve Midjourney gibi araçların kamuya açıldığı dönemle örtüşmekte ve literatürdeki bu kırılma noktasına karşılık gelmektedir. Yayın sayısı 2024–2025 döneminde en yüksek değerine ulaşmış; 2026 yılındaki görece azalma ise yılın henüz tamamlanmamış olmasıyla açıklanmaktadır. Bu dağılım, GenAI araçlarına yönelik akademik ilginin teknolojik gelişmelerle paralel bir seyir izlediğine ve alanda araştırma yoğunluğunun giderek arttığına işaret etmektedir. (Şekil 1)



Şekil 1. *Yıllık bilimsel üretim dağılımı (2016–2026). (Web of Science verilerinden biblioshiny ile üretilmiştir.)*

4.2. Tematik yapı ve kümelenmeler

Tematik harita analizi, alandaki araştırma temalarını merkezi ve gelişimsel konumlarına göre dört kadrana yerleştirmektedir (Şekil 2). Motor temalar (yüksek merkezilik, yüksek yoğunluk) alanın hem ilgisini çeken hem de iç bağlantısı güçlü olan konularını oluşturmaktadır.

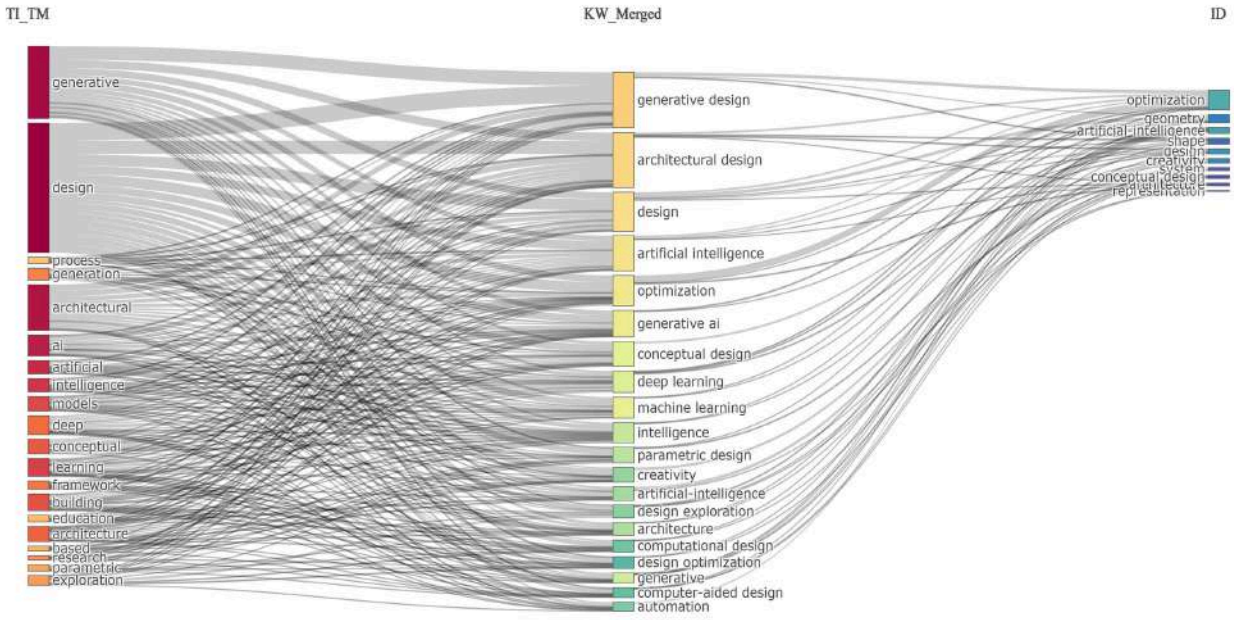


Şekil 2. *Tematik harita: Araştırma temalarının merkezilik ve yoğunluk eksenlerinde dağılımı.*

Tematik haritaya göre 'conceptual design', 'daylighting performance' ve 'architectural design' temaları motor temalar arasında yer almakta; bu temalar hem alan için kritik öneme sahip hem de kendi içinde güçlü birer araştırma kümesi oluşturmaktadır. 'Geometry', 'shape' ve 'envelope' ise yüksek merkeziliğe sahip temel temalar olarak belirginleşmektedir. Buna karşın 'design', 'artificial-intelligence' ve 'layout' kavramları alt-sol kadranda konumlanmakta; bu durum söz konusu temaların ya yeni ortaya çıkan ya da henüz yeterince gelişmemiş araştırma alanları olduğuna işaret etmektedir.

4.3. Anahtar kelime ağı analizi

Anahtar kelime ilişki ağı, başlık terimleri, birleştirilmiş anahtar kelimeler ve atıf indeksi kategorileri arasındaki akış ilişkisini görselleştirmekte; alandaki kavramsal yoğunlaşma noktalarını ve tematik bağlantıları ortaya koymaktadır. Şekil 3, 'generative', 'design' ve 'architectural' terimlerinin başlık düzeyinde baskın olduğunu; anahtar kelime düzeyinde ise 'generative design', 'architectural design' ve 'artificial intelligence' kümeleri etrafında yoğunlaşma gerçekleştiğini göstermektedir. Bu örüntü, alanın belirgin biçimde üretici tasarım–mimarlık kesişiminde konumlandığına ve yapay zeka ile kavramsal tasarım kavramlarının artan ağırlık kazandığına işaret etmektedir.



Şekil 3. *Başlık terimleri, anahtar kelimeler ve atıf indeksleri arasındaki ilişki ağı.*

4.4. GenAI Araçlarının Erken Kavramsal Aşamada Sunduğu Fırsatlar

Literatür, GenAI araçlarının özellikle erken kavramsal tasarım aşamasında fikir üretimi, alternatif keşfi ve görsel iletişim açısından önemli fırsatlar sunduğunu göstermektedir. Çalışmalar; metin-görsel modeller, büyük dil modelleri, difüzyon tabanlı sistemler ve üretici tasarım araçlarının tasarım sürecini hızlandırdığını, geniş çözüm uzaylarının keşfini desteklediğini ve yaratıcı düşünme süreçlerine katkı sağladığını ortaya koymaktadır. Ayrıca bazı araştırmalar, bu araçların mimar ile kullanıcı arasındaki görsel iletişimi güçlendirdiğini ve üretici özgünlüğü destekleyen yeni iş akışları oluşturduğunu vurgulamaktadır. İlgili çalışmaların araç, uygulama alanı ve sunduğu fırsatlar bağlamındaki karşılaştırmalı özeti Tablo 1'de görülmektedir.

Tablo 1. Çalışmalarda GenAI araçlarının erken kavramsal aşamada sunduğu fırsatlar

Kaynak	Kullanılan Araç / Model	Uygulama	Fırsatlar
Alamasi (2026)	*Genel GenAI araçları (deneysel)*	Mimarlık öğrencileriyle deneysel çalışma; yaratıcılık, zaman verimliliği ve kalite boyutları	Üç boyutun tamamında anlamlı olumlu katkı; zaman verimliliği
Tan vd. (2024)	*Midjourney (metin→görsel)*	Mimarların ıraksak ve yakınsak düşünce süreçlerini içeren tasarım metodolojisi	Alternatif keşfi, hızlandırılmış fikir üretimi
Arisman (2024)	*Üretici tasarım araçları*	Şematik tasarım aşamasında mimarların kullanım aracı	Geniş form alternatifi
Cai vd. (2023)	*LLM + görsel üretim*	Semantik çeşitlilik sağlayan alternatiflerin üretimi	Alternatif keşfi, üretici özgünlüğü artırıcı etki
Li vd. (2025)	*GAN, VAE, Difüzyon modelleri*	Farklı model mimarilerinin hangi tasarım adımına uygun olduğunun sistematik haritalandırması	Erken tasarım aşamasında keşif aracı
Mukkava ara vd. (2020)	*Parametrik üretici tasarım*	Konut bloğu için üretici tasarım çerçevesi; konfigürasyonların otomatik oluşturulması	Keşif genişliği ve hızlandırılmış fikir üretimi
Sebestyen vd. (2023)	*Koşullu VAE (CVAE)*	Semantik etiketlerle tanımlanmış interaktif tasarım alanı	Sezgisel ve keşfedilebilir bir tasarım alanı
Berseth vd. (2019)	*Çeşitli çözüm keşif algoritması*	Mimari tasarımda geniş ve çeşitli çözüm uzayının interaktif keşfi	Tasarımcı tercihlerine göre çeşitlilik
Jo vd. (2024)	*Yerel kimlik eğitimli difüzyon modeli*	Bölgeye özgü sokak görüntüleriyle eğitilmiş model; erken aşama cephe render alternatifleri üretimi	Görsel iletişim kalitesi, müşteri iletişiminde ve tasarım

Kaynak	Kullanılan Araç / Model	Uygulama	Fırsatlar
			değerlendirmesinde kullanılabilir çıktı
Gardini (2025)	*GenAI aracı (metin/eskiz/3B)*	Metin, eskiz ve 3B model girdileriyle test; görsel çıktı kalitesi ve pratik kullanılabilirlik	Alternatif keşfi, görsel iletişim kalitesi
Tholander vd. (2023)	*GPT-3*	Tasarım atölyelerinde GPT-3 ile eskiz, düşünme ve konuşma; tasarım ideasyon sürecindeki rolü	Üretici düşünce desteği
Zhang vd. (2024)	*GenAI + fiziksel modeller (hibrit)*	Fiziksel prototip ve GenAI çıktısını birleştiren hibrit prototipleme yöntemi	Üretici düşünce desteği
Hikmet & Ozay (2026)	*GenAI araçları (eğitim bağlamı)*	Mimarlık öğrencilerinin YZ ile iş birliği süreçleri	Üretici özgünlüğü artırıcı etki

4.5. Sınırlılıklar ve Kısıtlar

Son yıllarda üretken yapay zekânın mimarlık alanındaki kullanımına yönelik çalışmalar hızla artmış olsa da, literatür mevcut sistemlerin bağlam duyarlılığı, kullanıcı denetimi ve BIM/CAD entegrasyonu gibi kritik alanlarda çeşitli sınırlılıklar taşıdığını göstermektedir. Ayrıca yaratıcı kontrolün korunması, özgünlük üretimi ve araç bağımlılığı gibi konular da tartışmanın önemli eksenleri arasında yer almaktadır. Bu kapsamda ilgili çalışmaların araç, uygulama alanı ve tespit edilen kısıtlar bağlamındaki karşılaştırmalı özeti Tablo 2'de sunulmuştur.

Tablo 2. Çalışmalarda GenAI araçlarının erken kavramsal aşamadaki sınırlılıkları ve kısıtları

Kaynak	Kullanılan Araç / Model	Uygulama	Kısıtlar
Xu vd. (2024)	*Stable Diffusion (fine-tuning deneyi)*	Metin-görsel modelleri kat sayısı parametreleriyle test etme	Özgün mimari parametreleri işleme kısıtlılığı
Khan vd. (2025)	*Çoklu GenAI araçları — karşılaştırmalı değerlendirme*	Mevcut modellerin mimari kriter üzerinden (oran, bağlam, malzeme, strüktür vb.) test edilmesi	Bağlam duyarlılığı zayıflığı, modeller mimari özgünlük açısından yapısal olarak yetersiz
Jang vd. (2023)	*GPT serisi + BIM araçları (Revit)*	Doğal dille BIM modeli geliştirme, interaktif tasarım	Entegrasyonda mevcut altyapıya uyum güçlükleri
Zhong vd. (2025)	*Eskiz girdili ajansal 3B modelleme çerçevesi*	Mevcut araçların kara kutu niteliği ve 3B modelleme çerçevesi	GenAI çıktılarının üretim aracı olarak kullanım kısıtlılığı, mimarın çıktı üzerindeki kontrol güçlükleri
Giuliani vd. (2024)	*GenAI araçları — yaratıcılık ve sürdürülebilirlik bağlamı*	GenAI ile yürütülen yaratıcı iş akışlarının incelenmesi; kontrol, özgünlük ve bağımlılık boyutları	Kontrol yitimi, özgünlük eksikliği ve otomasyona aşırı bağımlılık riskleri
Cao vd. (2025)	*Stable Diffusion — mimari stüdyo iş akışı*	Mimari tasarım stüdyosunda, tasarım süreci ve öğrenme deneyimi üzerindeki etkisi	Stüdyo ortamında kontrollü kullanım protokolleri olmaksızın benimsenmesi riski
Labuda (2025)	*Kavramsal mimari tasarım — kuramsal tartışma*	GenAI karşısında mimarın rekabet avantajını sorgulama; buluşsal yöntemler ve özgünlük kavramlarını tartışma	Özgünlüğü koruyamama kısıtları

Kaynak	Kullanılan Araç / Model	Uygulama	Kısıtlar
Kim vd. (2024)	*YZ ile mimari özellik kodlama*	Mevcut genel modellerin mimari tipoloji ve özellikleri yeterince kodlayıp kodlayamamasının araştırılması	Genel modellerin mimari kimliği ve özgünlüğü koruyamama kısıtları
Agkathidis vd. (2024)	*Midjourney, DALL-E, Stable Diffusion — eğitim bağlamı*	Araçların mimarlık öğrencilerinin form arama süreçlerine entegrasyonunu deneme	Özgünlük kaygısı, araçların eleştirel filtre olmadan kullanımında yaratıcı özerklik yerine araç bağımlılığı gelişmesi

5. Tartışma

Sistematik taramanın ortaya koyduğu bulgular, GenAI araçlarının erken kavramsal tasarım aşamasında önemli bir potansiyel taşıdığını, ancak bu potansiyelin gerçekleşmesinin büyük ölçüde araçların nasıl konumlandırıldığına bağlı olduğunu göstermektedir. Temel tartışma eksenlerinden biri, mimarın araçla kurduğu ilişkinin niteliğidir. Araçların özerk bir üretici olarak değil, iş birliğine dayalı bir tasarım ortağı olarak konumlandırıldığı durumlarda süreç verimliliği ve tasarım kalitesi açısından daha olumlu sonuçlar elde edilmektedir (Saadi vd., 2023; Gmeiner vd., 2023). Bu bulgu, 'artırılmış zeka' paradigmasıyla örtüşmekte ve yapay zekanın mimarın karar verme kapasitesini ikame etmesi yerine güçlendirmesi gerektiğini savunan kuramsal çerçevelerle uyuşmaktadır (Salamanca vd., 2023).

Yıllık bilimsel üretim analizi, 2022 sonrasında yaşanan yayın artışının, araştırma ilgisinin teknolojik gelişmelerle yakından ilişkili olduğunu göstermektedir. Öte yandan tematik haritada 'design' ve 'artificial-intelligence' temalarının henüz gelişmekte olan kategoride konumlanması, konunun araştırma olgunluğunun hâlâ erken aşamada olduğuna işaret etmektedir.

Eğitim bağlamında yürütülen çalışmalar (Agkathidis vd., 2024; Basarir, 2022; Özorhon, 2025), GenAI araçlarının mimarlık öğrencilerinin tasarım süreçlerine entegre edilmesinin kritik metodolojik sorular doğurduğunu ortaya koymaktadır. Özellikle yaratıcı özerklik ve eleştirel değerlendirme becerilerinin nasıl korunacağı, pedagojik açıdan henüz tam olarak yanıtlanamamış bir sorun olarak gündemdeki yerini korumaktadır.

6. Sonuç

Bu çalışma, GenAI araçlarının mimari tasarımın erken kavramsal aşamasında tasarım asistanı olarak taşıdığı potansiyeli ve sınırlılıkları 109 kaynak üzerinden sistematik biçimde değerlendirmiştir. Elde edilen bulgular, bu araçların fikir üretimini hızlandırma, tasarım seçeneği keşfini genişletme, görsel iletişimi güçlendirme ve yaratıcı düşünceyi destekleme kapasitesine sahip olduğunu ortaya koymaktadır.

Bununla birlikte, bağlam duyarlılığı eksiklikleri, BIM/CAD entegrasyon güçlükleri, çıktı kontrolü sorunları ve tasarım özgünlüğüne ilişkin kaygılar bu araçların tek başına yeterli olmadığına işaret etmektedir. Bu bağlamda, GenAI araçlarının tasarım sürecinde yaratacağı değer, büyük ölçüde bu araçların nasıl konumlandırıldığına bağlıdır. Özerk üreticiden iş birliğine dayalı tasarım ortağına uzanan eksenin iş birliği kısmında konumlanmak, hem süreç verimliliği hem de çıktı kalitesi açısından belirleyicidir.

Mimarlık pratiği ve eğitimi açısından, GenAI okuryazarlığının mimarlık eğitiminin temel bir bileşeni haline getirilmesi, farklı tasarım aşamalarına uygun araç-görev eşleşmelerinin belirlenmesi ve bu araçların döngüsel ve yinelemeli bir tasarım sürecine entegre edilmesi çıkarımları yapılmaktadır. Gelecek araştırmalar; gerçek proje bağlamlarında yürütülen deneysel çalışmalar, uzunlamasına izleme çalışmaları ve farklı kültürel bağlamlarda karşılaştırmalı analizler yoluyla bu bilgi tabanını genişletebilir.

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MİCROBİAL MODULATİON OF ETHYLENE BİOSYNTHESİS İN CLİMACTERİC FRUİTS: MECHANİSTİC INSİGHTS AND POSTHARVEST APPLİCATİONS OF ACC DEAMİNASE-PRODUCİNG PGPR

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Abstract

Ethylene, the primary determinant of postharvest quality losses in climacteric fruits, is the main phytohormone that accelerates the ripening process, particularly in crops such as tomatoes (Solanum lycopersicum), bananas (Musa spp.), and apples (Malus domestica). In this study, focusing on the regulation of ethylene biosynthesis via microbial pathways, the role of plant growth-promoting rhizobacteria (PGPR) was comprehensively evaluated. In particular, it was demonstrated that bacteria producing ACC deaminase suppress ethylene production by degrading 1-aminocyclopropane-1-carboxylic acid (ACC), the precursor molecule of ethylene, and delay the climacteric respiration peak. Studies on tomatoes, bananas, and apples indicate that species of Pseudomonas, Bacillus, and Methylobacterium not only regulate ethylene biosynthesis but also extend shelf life by reducing cell wall degradation, respiration rates, and oxidative stress. Additionally, it has been determined that these bacteria activate antioxidant enzyme systems and modulate hormone interactions. In conclusion, PGPR applications offer a promising biotechnological approach for managing post-harvest physiology in climacteric fruits using sustainable and chemical-free methods.

Keywords: Climacteric fruits, Ethylene biosynthesis, ACC deaminase, Plant growth-promoting rhizobacteria (PGPR), Postharvest physiology.

KLİMAKTERİK MEYVELERDE ETİLEN BİYOSENTEZİNİN MİKROBİYAL MODÜLASYONU: ACC DEAMİNAZ ÜRETEN PGPR'NİN MEKANİSTİK ANALİZİ VE HASAT SONRASI UYGULAMALARI

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Özet

Klimakterik meyvelerde hasat sonrası kalite kayıplarının temel belirleyicisi olan etilen, özellikle domates (*Solanum lycopersicum*), muz (*Musa spp.*) ve elma (*Malus domestica*) gibi ürünlerde olgunlaşma sürecini hızlandıran başlıca fitohormondur. Bu çalışmada, etilen biyosentezinin mikrobiyal yollarla düzenlenmesi üzerine odaklanılarak, bitki büyümesini teşvik eden rizobakterilerin (PGPR) rolü kapsamlı biçimde değerlendirilmiştir. Özellikle ACC deaminaz üreten bakterilerin, etilenin öncül molekülü olan 1-aminosiklopropan-1-karboksilik asidi (ACC) parçalayarak etilen üretimini baskıladığı ve klimakterik solunum pikini geciktirdiği ortaya konmuştur. Domates, muz ve elma üzerine yapılan çalışmalar, *Pseudomonas*, *Bacillus* ve *Methylobacterium* türlerinin hem etilen biyosentezini düzenlediğini hem de hücre duvarı yıkımını, solunum hızını ve oksidatif stresi azaltarak raf ömrünü uzattığını göstermektedir. Ayrıca bu bakterilerin antioksidan enzim sistemlerini aktive ettiği ve hormonlar arası etkileşimleri modüle ettiği belirlenmiştir. Sonuç olarak, PGPR uygulamaları, klimakterik meyvelerde hasat sonrası fizyolojinin sürdürülebilir ve kimyasal içermeyen yöntemlerle yönetilmesinde umut verici bir biyoteknolojik yaklaşım sunmaktadır.

Anahtar Kelimeler: Klimakterik meyveler, Etilen biyosentezi, ACC deaminaz, Bitki büyümesini teşvik eden rizobakteriler (PGPR), Hasat sonrası fizyoloji

1. Giriş ve Ekonomik Önem

Bu akademik inceleme, taze meyve ve sebzelerin korunmasında kritik bir rol oynayan etilen yönetimi stratejilerini kapsamlı bir şekilde ele almaktadır. Bitkiler tarafından doğal olarak üretilen bir hormon olan etilenin, gıdaların olgunlaşma ve bozulma süreçlerini nasıl hızlandırdığı detaylandırılmaktadır. Bu çalışma ile, bu gazın olumsuz etkilerini azaltmak için kullanılan kontrollü atmosfer teknolojisi, potasyum permanganat ve ozonla oksidasyon gibi çeşitli kimyasal ve fiziksel yöntemleri açıklamaktadır. Ayrıca, bu teknolojilerin raf ömrünü uzatma ve gıda kalitesini koruma konusundaki başarısı ile yüksek maliyet gibi uygulama zorlukları karşılaştırılmaktadır. Kaynaklar, özellikle hasat sonrası kayıpları en aza indirmek için geliştirilen yeni nesil sistemlerin bilimsel temellerine odaklanmaktadır. Sonuç olarak, gıda endüstrisinde tazeliği muhafaza etmek adına başvurulan hem geleneksel hem de modern mühendislik çözümleri bütüncül bir perspektifle sunulmaktadır.

Klimakterik meyveler (domates, muz, elma vb.), olgunlaşma aşamasında ani bir **otokatalitik etilen (C_2H_4) artışı** ve solunum sıçraması ile karakterize edilirler **(Soneji ve ark., 2024).** Bu süreç meyvenin tat ve aroma kazanması için gerekli olsa da, hızlı yaşlanmaya ve bozulmaya yol açarak hasat sonrası kayıpların gelişmekte olan ülkelerde %50'ye ulaşmasına neden olmaktadır **(Mubarok ve ark., 2023).** Küresel çapta bu ekonomik kaybın yıllık 750 milyar dolar civarında olduğu tahmin edilmektedir **(Beer ve ark., 2026).** Bu kayıpları önlemek için etilen biyosentezini baskılayan sürdürülebilir stratejiler, özellikle **ACC deaminaz üreten PGPR** kullanımı akademik ve endüstriyel olarak büyük önem kazanmıştır **(Shahid ve ark., 2023).**

1. Klimakterium ve Klimakterik Meyvelerin Fizyolojisi

Klimakterium, meyvelerin olgunlaşma sürecinin başlangıcında solunum hızlarında ve etilen üretimlerinde meydana gelen ani ve belirgin artışla karakterize edilen fizyolojik bir evredir (Fidan ve Söylemezoğlu, 1995). Bahçe bitkileri, hasat sonrası solunum davranışlarına göre "klimakterik" ve "klimakterik olmayan" (non-klimakterik) olmak üzere iki ana gruba ayrılırlar (Söylemezoğlu, 1998). Bu terim ilk kez 1924 yılında Kidd ve West tarafından elmalar üzerinde yapılan çalışmalarla literatüre kazandırılmıştır (Söylemezoğlu, 1998).

Klimakterik Meyvelerin Fizyolojik Özellikleri

Klimakterik meyvelerin fizyolojisi ve olgunlaşma mekanizmaları şu temel özelliklerle tanımlanır:

Solunum Tepe Noktası (Klimakterik Yükseliş): Bu meyveler, olgunlaşmanın erken dönemlerinde solunum hızlarında dramatik bir artış gösterirler (Söylemezoğlu, 1998). Solunumun en yüksek seviyeye ulaştığı bu noktaya "klimakterik tepe noktası" denir ve bu aşamadan sonra solunum hızı tekrar düşmeye başlar (Söylemezoğlu, 1998).

Otokatalitik Etilen Üretimi : Klimakterik meyvelerin en karakteristik özelliklerinden biri, belirli bir etilen eşiği aşıldığında sistemin kendi kendini besleyerek çok yüksek miktarda etilen üretmeye başlamasıdır (Fidan ve Söylemezoğlu, 1995). Bu durum, etilenin kendi sentezini uyarması (otokatalitik üretim) olarak bilinir ve bitki fizyolojisinde "Sistem 2" olarak adlandırılır (Fidan ve Söylemezoğlu, 1995).

Etilen Hassasiyeti: Klimakterik meyveler, dışarıdan uygulanan etilene karşı oldukça hassastır; dışsal etilen, klimakterik yükselişi öne çekerek olgunlaşma sürecini tetikleyebilir (Sezer ve Ayhan, 2017). Olgunlaşma ilerledikçe bu meyvelerde etilen üretim miktarı tür ve çeşide göre binlerce kat artabilir (Söylemezoğlu, 1998).

Hızlı Biyokimyasal Değişimler: Solunum tepesi ile eş zamanlı olarak meyvelerde klorofilin parçalanması sonucu renk değişimi, aroma maddelerinin oluşumu, nişastanın şekere dönüşümü ve pektin yıkımı sonucu meyve eti yumuşaması gibi değişimler hızla gerçekleşir (Ergun, 2005; Söylemezoğlu, 1998).

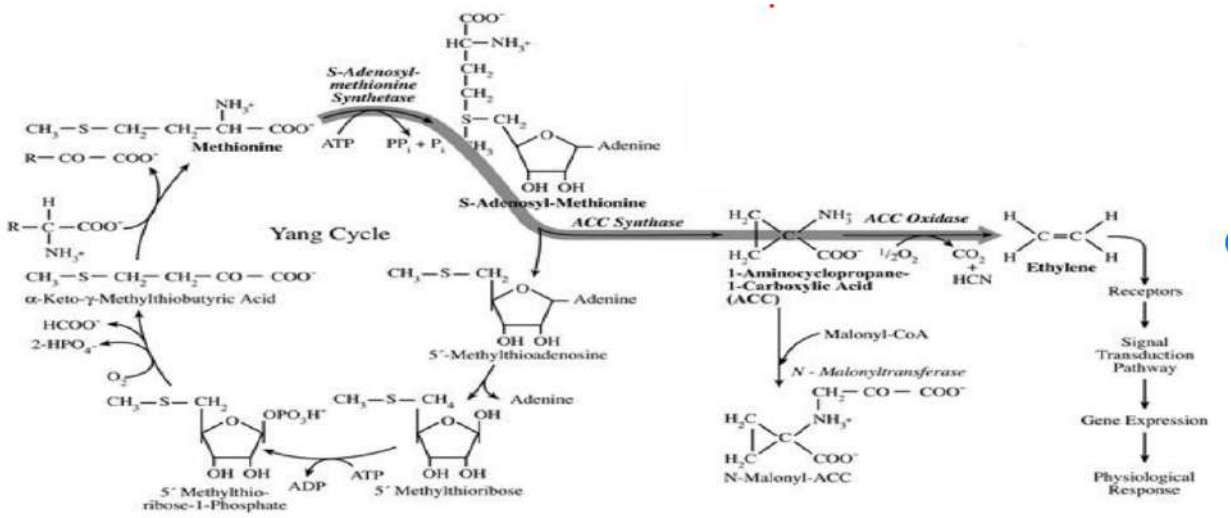
Hasat Sonrası Olgunlaşma Yeteneği: Klimakterik meyveler, "fizyolojik olgunluk" aşamasına ulaştıktan sonra hasat edildiklerinde, ağaçtan koparılmış olsalar dahi yeme olgunluğuna ulaşabilirler (Söylemezoğlu, 1998). Ancak bu durum, hasat sonrası ömürlerinin genellikle sınırlı olmasına ve ürünlerin hızla yumuşayıp bozulmasına neden olur (Meral ve ark., 2024; Söylemezoğlu, 1998).

Klimakterik meyvelere örnekler: Elma, kayısı, muz, domates, şeftali, armut, erik, nektarin ve avokado bu grupta yer alan başlıca ürünlerdir (Sezer ve Ayhan, 2017; Meral ve ark., 2024). Örneğin, domates ve kayısı gibi ürünler yüksek etilen hassasiyetleri nedeniyle hasat

sonrası süreçte hızla olgunlaşıp yumuşama eğilimindedirler (Sedef Yeni Nesil Endüstriyel Çözümler, 2017; Meral ve ark., 2024).

2. Etilen Biyosentezi: Yang Döngüsü ve Düzenleyici Mekanizmalar

Bitkilerde etilen sentezi, **Yang Döngüsü** olarak bilinen metiyonin-ACC yolu üzerinden gerçekleşir:



Şekil 1: Bitkilerde Etilen Biyosentez Yolu ***(Yang and Hoffman (1984) and Schaller and Kieber (2002).)***

Bu döngüde **ACC Sentaz (ACS),** biyosentezin hız kısıtlayıcı adımıdır **(Soneji ve ark., 2024).** Klimakterik meyvelerde iki sistemli bir model işler: **Sistem 1**, olgunlaşma öncesi bazal üretimi; **Sistem 2** ise olgunlaşma sırasında tetiklenen yüksek düzeydeki otokatalitik üretimi temsil eder **(Vilhena ve ark., 2023).**

3. ACC Deaminaz (ACCD) Üreten PGPR'nin Mekanistik Analizi

ACC deaminaz üreten bakteriler, bitkilerde etilen seviyelerini düzenleyen "stres modülatörleri" olarak işlev görürler **(Shahid ve ark., 2023).**

- **Katalitik Reaksiyon:** ACCD enzimi, etilenin doğrudan öncüsü olan ACC'yi geri dönüşümsüz olarak **α-ketobütirat ve amonyağa** parçalar **(Gupta ve ark., 2022).**

- **ACC Lavabosu Etkisi:** Rizosferde veya meyve yüzeyinde bulunan bakteriler, dokulardan sızan ACC'yi kullanarak bitki içindeki ACC havuzunu azaltır ve böylece Sistem 2 etilen üretiminin başlamasını geciktirir **(Shahid ve ark., 2023).**
- **Kinetik Dinamikler:** ACC oksidazın (ACO) ACC'ye ilgisi, ACC deaminazdan daha yüksektir. Bu nedenle etkili bir modülasyon için bakterilerin meyve yüzeyinde yüksek yoğunlukta bulunması gerekir **(Soneji ve ark., 2024)**.

4. PGPR Modülasyonunun Solunum Hızı ve Stres Enzimleri Üzerine Etkisi

PGPR uygulamaları, meyvenin fizyolojik stabilitesini iki ana mekanizma ile korur:

- **Solunum Hızının Düzenlenmesi:** ACCD aktivitesi, meyvenin klimakterik solunum sıçramasını geciktirerek karbonhidratların hızlı parçalanmasını ve ağırlık kaybını önler **(Beer ve ark., 2026)**. Örneğin domateslerde mikrobiyal tedavi, CO_2 çıkışını azaltarak doku sertliğini korur **(Shahid ve ark., 2023).**
- **Antioksidan Savunma (Metabolic Priming):** PGPR'ler, meyvenin iç savunma sistemini hazırlayarak **Süperoksit Dismutaz (SOD), Katalaz (CAT) ve Peroksidaz (POD)** gibi enzimlerin aktivitelerini artırır **(Gupta ve ark., 2022).** Bu durum, lipid peroksidasyonunun bir göstergesi olan malondialdehit (MDA) seviyelerini düşürerek meyveyi oksidatif hasara karşı dirençli kılar **(Shahid ve ark., 2023).**

5. Ekonomik Önemi Olan Meyvelerde Hasat Sonrası Uygulamalar

5.1. Domates (Solanum lycopersicum)

Domates, üretiminin yaklaşık %20'sini çürüme nedeniyle kaybeden hassas bir meyvedir **(Mubarok ve ark., 2023).**

- **Önerilen Suşlar:** ***Pseudomonas sp. UW4*** ve ***Pseudomonas fluorescens YsS6*** suşlarının domateslerde raf ömrünü **15 güne kadar** uzattığı ve meyve sertliğini koruduğu rapor edilmiştir **(Shahid ve ark., 2023).**

*5.2. Muz (*Musa spp.*)*

Muzlar, en yüksek hasat sonrası kayıp oranına (%22-30) sahip ürünler arasındadır **(Beer ve ark., 2026).**

- **Uygulama:** ***Bacillus subtilis MBD 133*** suşu stres etilenini azaltmada etkilidir **(Gupta ve ark., 2022).** Ayrıca geliştirilen **CISH-METWASH** organik formülasyonu, muz raf ömrünü **45 güne** çıkarmış ve antraknoz hastalığını tamamen baskılamıştır **(Beer ve ark., 2026).**

*5.3. Elma (*Malus domestica*)*

Elma endüstrisinde ACCD aktivitesi **1000 nmol α-KB/mg/h üzerinde olan** suşların kullanımı önerilmektedir **(Soneji ve ark., 2024).**

- **Etki:** Mikrobiyal modülasyon, 1-MCP gibi kimyasal engelleyicilerin aksine etileni tamamen yok etmediği için **meyvenin doğal aroma profilinin (volatil esterler)** korunmasına izin verir **(Vilhena ve ark., 2023)**.

6. Sonuç ve Gelecek Perspektifleri

ACC deaminaz üreten PGPR'ler, hasat sonrası korumada **çevreci ve toksik olmayan** güçlü bir strateji sunmaktadır **(Shahid ve ark., 2023).** Gelecekte, birden fazla özelliğe sahip **sentetik mikrobiyal toplulukların (SynComs)** kullanımı ve nanoteknolojik paketleme sistemleri ile bu teknolojinin etkinliğinin artırılması hedeflenmektedir **(Soneji ve ark., 2024).**

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INFLUENCE OF FIBER LENGTH, FIBER CONTENT, AND AGGREGATE TYPE ON THE DRYING SHRINKAGE OF 3D PRINTABLE CONCRETE MIXTURES

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ABSTRACT

3D printable concrete technology offers an innovative approach and significant potential for the construction industry. Due to its additive manufacturing process that eliminates the need for formwork, it reduces costs, time, and material waste. However, the absence of formwork, the absence of coarse aggregate, and the relatively high binder ratio increase the risk of drying shrinkage in these mixtures. In 3D printable concrete mixtures, fiber reinforcement is generally preferred over conventional reinforcement to enhance drying shrinkage performance and ensure ductility. In this study, the drying shrinkage performance of thirteen 3D printable concrete mixtures was investigated. The drying shrinkage performance of the mixtures was evaluated depending on different polypropylene fiber lengths (3, 6 and 12 mm), polypropylene fiber content (0.2%, 0.4% and 0.6%), and the use of recycled concrete aggregate (0% and 100%). In conclusion, it was determined that short fibers with lengths of 3 and 6 mm improved the 6-month drying shrinkage performance of 3D printable concrete mixtures by 17-31%. It was observed that the drying shrinkage performance of the mixtures varied depending on the fiber length as the fiber content increased. In mixtures containing fibers with lengths of 6 and 12 mm, it was determined that increasing the fiber dosage by up to 0.4% improved the drying- shrinkage performance by 15% and 24%, respectively. Conversely, in mixtures with 3 mm fibers, increasing the fiber content reduced the drying shrinkage performance. In terms of drying shrinkage performance, the optimum mixtures were determined to be those containing 0.4% fiber with a length of 6 mm and those containing 0.2% fiber with a length of 3 mm. In addition, it was measured that using 100% recycled concrete aggregate instead of limestone aggregate negatively affects the drying shrinkage performance of the mixtures by 48-78%.

Keywords: 3D printable concrete, polypropylene fiber, recycled concrete aggregate, drying-shrinkage

1. INTRODUCTION

Developed to support digitalization processes and increase efficiency in the construction industry, additive manufacturing technology has become a rapidly growing research and application area (Zhang et al., 2023). This technology stands out with advantages such as offering design flexibility, shortening production time, and saving labor costs (Şahin, Akgümüş, et al., 2025; Şahin, Kaya, et al., 2025; Şahin & Mardani, 2023). Also, 3D printable concrete (3DPC) mixtures present significant challenges, such as a high tendency towards shrinkage and the associated risk of cracking (Şahin et al., 2024). The drying-shrinkage behavior of these mixtures is negatively affected by factors such as low confinement conditions due to the absence of formwork, high water evaporation rate, the absence of coarse aggregates, and the high binder ratio (Ghourchian et al., 2018; Zhang et al., 2023; Zhang & Xiao, 2021).

In traditional concrete, the use of reinforcement is common to ensure dimensional stability (Kaya et al., 2023; Mardani-Aghabaglou et al., 2016). However, the lack of formwork in 3DPC mixtures makes reinforcement placement more difficult. Accordingly, Alonso-Canon et al., (2022) classified different reinforcement techniques such as retrofitted reinforcement, pre-positioned reinforcement, cabling during printing, and in-process mesh reinforcement. However, these methods have not gained widespread adoption because they limit design flexibility, increase equipment requirements, and complicate the production process. Given these limitations, fiber reinforcement stands out as a more practical solution in 3DPC mixtures. Zhang et al., (2023), discussed the suitability of methods used to evaluate the shrinkage behavior of conventional concrete to 3DPC mixtures. This study indicates that the linear variable differential transformer (LVDT) method is not applicable to such mixtures due to the lack of regularly shaped molds. The laser sensor method is considered incompatible with the anisotropic nature of 3DPC mixtures because it only considers the linear distance change between two marked points on the sample surface. Furthermore, it has been stated that the digital image correlation (DIC) method is unsuitable because the spraying process used to create black-and-white patterns alters the evaporation conditions. As the literature indicates, there is no generally accepted standard or test protocol for 3DPC mixtures, and there is a significant need for research in this area. In this study, the 184-day drying-shrinkage performance of thirteen different 3DPC mixtures was investigated. The performance of the mixtures was evaluated depending on three different polypropylene fiber lengths (3, 6, and 12 mm), three different polypropylene fiber ratios (0.2%, 0.4%, and 0.6%), and the use of recycled concrete aggregate (0% and 100%).

2. MATERIALS AND METHODS

In this study, thirteen different 3DPC mixtures were produced, and their 184-day drying shrinkage values were determined. The materials used in preparing the mixtures and their mixing ratios are presented in Table 1. In mix design, cement, fly ash, silica fume, aggregate type (limestone aggregate and recycled concrete aggregate, RCA), polypropylene fiber quantity and length, and water-reducing admixture dosage were considered as independent variables.

Table 1. Mix proportions of 3D printable concrete

Mixture	Cement (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Limestone (kg/m^3)	Recycled concrete aggregate (RCA) (kg/m^3)	Water (kg/m^3)	Polypropylene fiber content (kg/m^3)	Polypropylene fiber length (mm)	Water-reducing admixture (kg/m^3)
1	450	350	0	1034.5	0	280	0	-	8.5
2	450	350	0	1029.4	0	280	3.6	3	8.5
3	450	350	0	1024.2	0	280	7.1	3	8.5
4	450	350	0	1019.1	0	280	10.7	3	8.5
5	450	350	0	1029.4	0	280	3.6	6	8.5
6	450	350	0	1024.2	0	280	7.1	6	8.5
7	450	350	0	1019.1	0	280	10.7	6	8.5
8	450	350	0	1029.4	0	280	3.6	12	8.5

9	450	350	0	1024.2	0	280	7.1	12	8.5
10	450	350	0	1019.1	0	280	10.7	12	8.5
11	450	350	0	0	993.4	280	7.1	6	3
12	423	350	27	0	981.1	280	7.1	6	4
13	409.5	350	40.5	0	973.8	280	7.1	6	5

To investigate the drying-shrinkage behavior of the mixtures, prismatic specimens with dimensions of 40×25×285 mm were extruded in two layers as illustrated in Figure 1. The samples were subjected to a 48-hour water cure and then stored in a chamber with 55% relative humidity. The length change of the prismatic samples was calculated using Equation 1 according to ASTM C 596-01 Standard.

$$S = \frac{L_1 - L}{L_0}.100 \qquad (1)$$

Here, S represents the shrinkage percentage of the sample, L_1 is the initial measurement value after removal from the curing pool, L is the periodic measurement value, and L_0 is the effective measurement length.



Figure 1. Shrinkage specimen and test setup

3. EXPERIMENTAL RESULTS AND DISCUSSION

The 184-day drying-shrinkage values of the mixtures produced within the scope of the study are shown in Figure 2. The rate of increase in length change due to shrinkage was high in all mixtures in the first few days, but showed a decreasing trend over time (Altun et al., 2018). The effect of fiber usage on drying-shrinkage values is shown in Figures 2-a, b and c. The use of polypropylene fibers generally improves the drying-shrinkage performance of 3DPC mixtures, but it has been observed that this improvement varies depending on fiber length and fiber ratio.

It was determined that mixtures containing fibers with a length of 3 mm showed an improvement of 19% to 31% in drying-shrinkage performance compared to the control mixture.

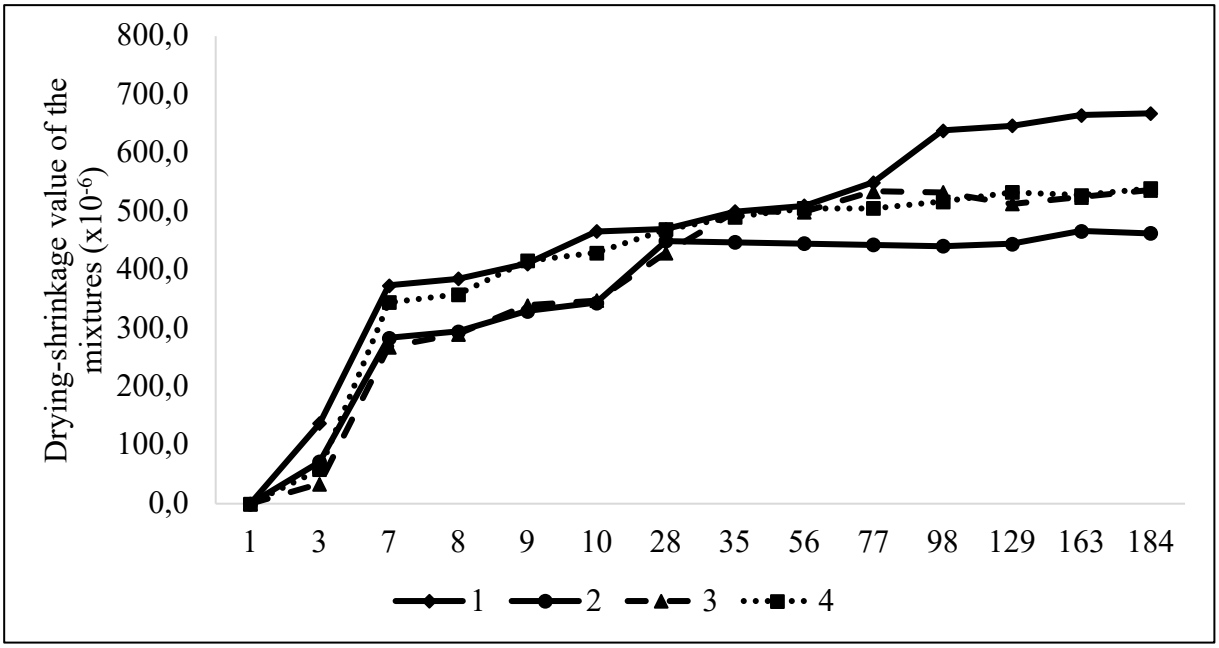
Mardani-Aghabaglou et al., (2019), state that the main reason for this improvement is that the fibers act as bridges between cracks, preventing crack propagation. Also, it was found that an increase in fiber content in this group negatively affected performance by 16%. This was attributed to agglomeration formation within the matrix and an increase in the air content of the mixtures due to the high fiber content. Nematollahi et al., (2017) and Saruhan, (2022), state that the fibers create an air-entraining effect by trapping air within the matrix, and this leads to additional voids. Furthermore, it is known that fibers with a length of 3 mm have a higher risk of breaking in the mixture compared to other fiber lengths. SEM images of the severed fibers are shown in Figure 3. The high breaking rate observed in

short fibers can be explained by their high surface area/volume ratio and limited capacity to bond with the matrix. In addition, their higher alignment ratio along the extrusion direction compared to other fiber lengths also contributes to this.

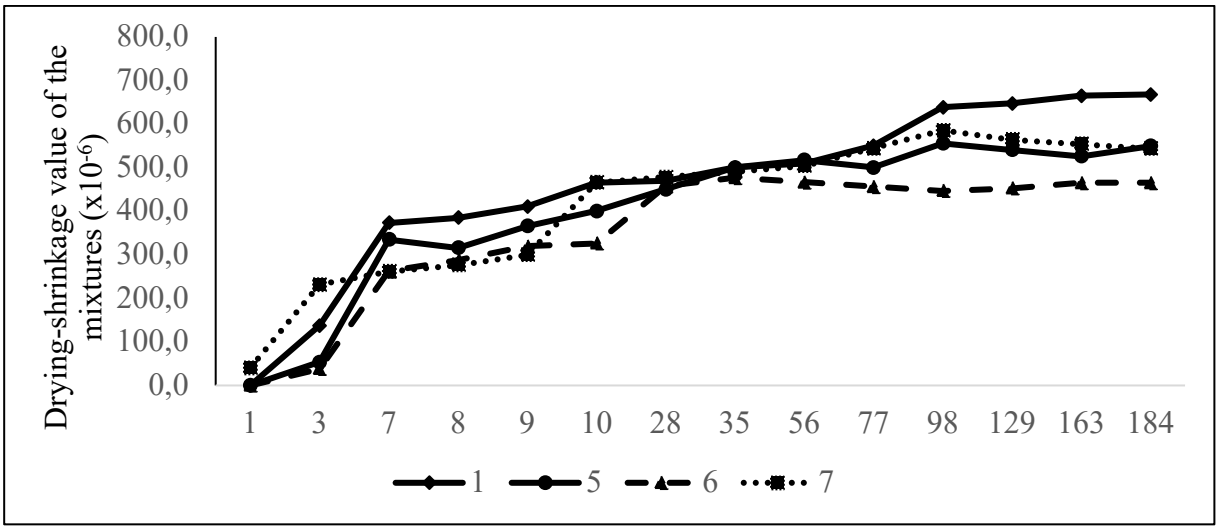
In mixtures containing 6 mm long fibers, a 17-31% increase in drying-shrinkage performance was measured compared to the control mixture. Increasing the fiber content up to 0.4% positively affected performance, while exceeding this percentage negatively impacted performance.

In mixtures containing 12 mm long fibers, unlike other fiber lengths, it was found that the drying-shrinkage performance was negatively affected by percentages ranging from 1% to 33% compared to the control mixture. This is attributed to long fibers intertwine and curl, causing clumping. The agglomerations that formed created additional voids within the matrix, negatively affecting the drying and shrinkage performance (Mardani-Aghabaglou et al. 2017). The curling observed in the 12 mm long fibers can be clearly seen in the SEM images presented in Figure 4.

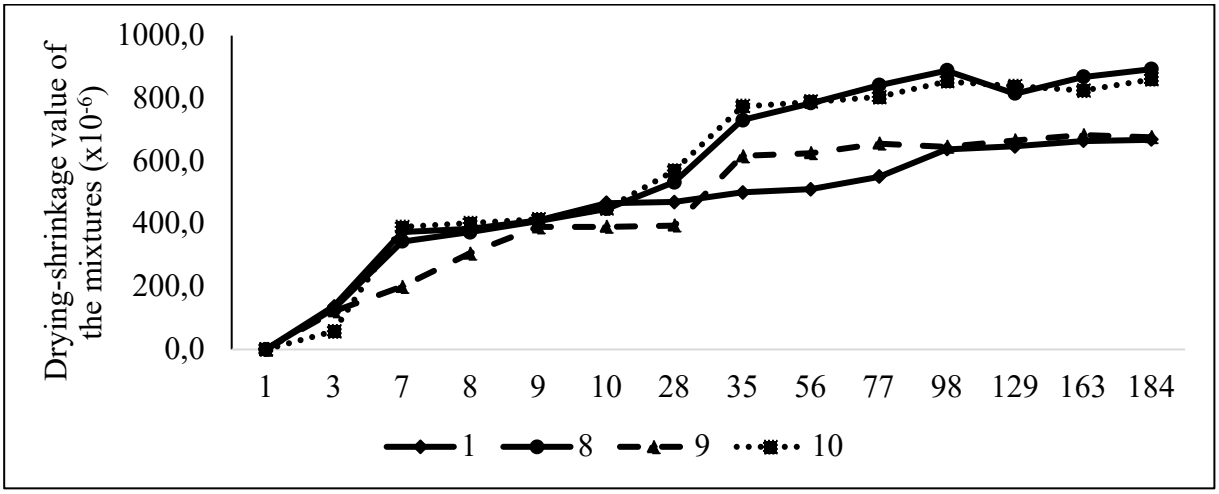
As shown in Figure 2-d, using 100% RCA instead of limestone aggregate resulted in a significant increase in the drying shrinkage values of the mixtures. This increase has been measured to vary between 46% and 78%. This can be explained by the fact that RCAs have a high water absorption capacity and exhibit lower rigidity characteristics. Silva et al., (2015), emphasize that the shrinkage performance of concrete mixtures is directly related to the strength and modulus of elasticity of the aggregate. In addition, it was determined that the use of silica fume negatively affected the drying-shrinkage performance of the mixtures by 22%. This negative effect is thought to stem from the increased water requirement due to the extreme fineness of silica fume (Mardani et al., 2025; Mardani-Aghabaglou et al., 2014; Şahin et al., 2024).


Drying-shrinkage value of the mixtures (x10-6)
800,0
700,0
600,0
500,0
400,0
300,0
200,0
100,0
0,0
1 3 7 8 9 10 28 35 56 77 98 129 163 184
1 2 3 4

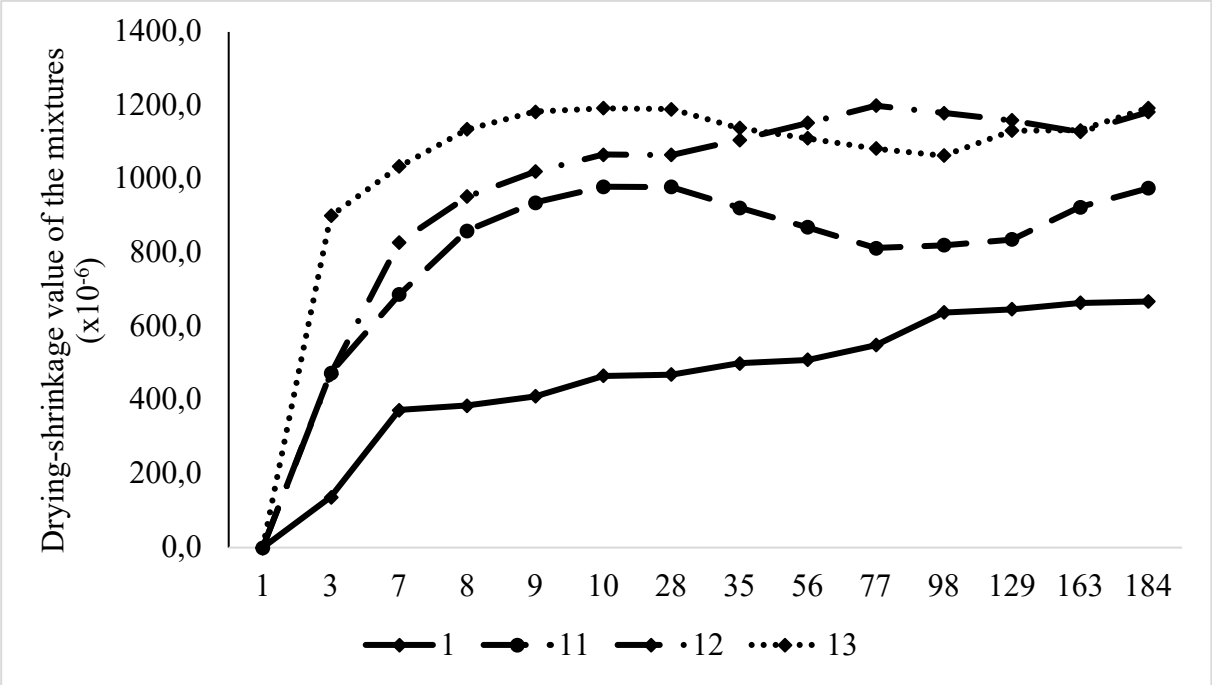
(a)


Drying-shrinkage value of the mixtures (x10-6)
800,0
700,0
600,0
500,0
400,0
300,0
200,0
100,0
0,0
1 3 7 8 9 10 28 35 56 77 98 129 163 184
1 5 6 7

(b)


Drying-shrinkage value of the mixtures (x10-6)
1000,0
800,0
600,0
400,0
200,0
0,0
1 3 7 8 9 10 28 35 56 77 98 129 163 184
1 8 9 10

(c)



(d)

Figure 2. Drying shrinkage values of the control mixture and mixtures containing (a) 3 mm fibers, (b) 6 mm fibers, (c) 12 mm fibers, and (d) RCA

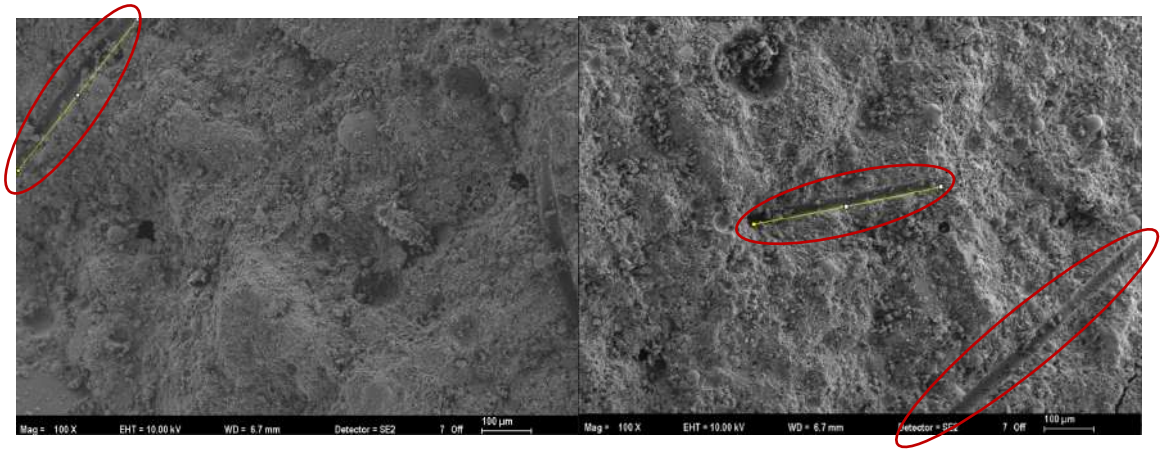


Figure 3. Illustration of the breaking state of fibers with a length of 3 mm

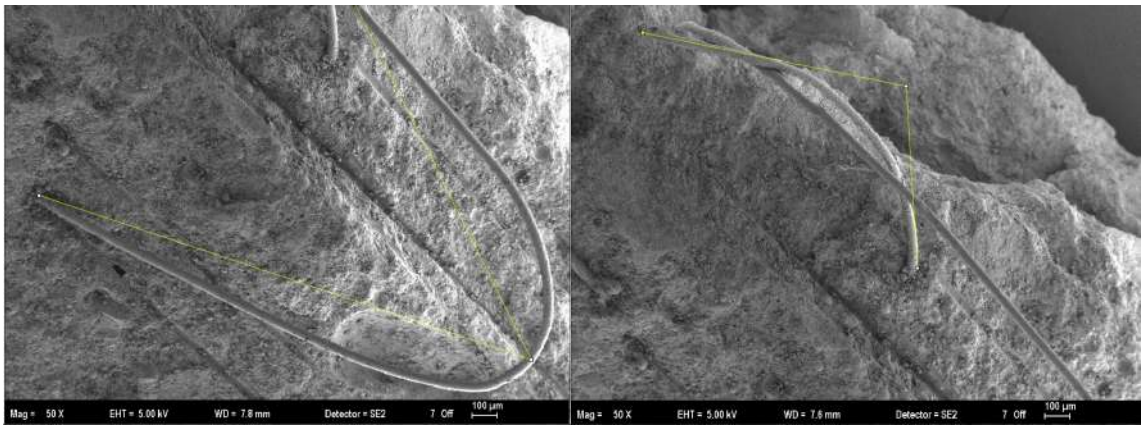


Figure 4. Microstructure image of fiber curl state in mixtures containing fibers with a length of 12 mm

4. CONCLUSIONS

Based on the materials used and experiments conducted within the scope of this study, the following results were obtained:

- While the use of polypropylene fibers generally improves the drying-shrinkage performance of mixtures, it has been determined that this improvement varies depending on fiber length and fiber ratio. Fibers with lengths of 3 and 6 mm were found to improve drying-shrinkage performance by 17-31% compared to the control mixture.
- The effect of increasing fiber ratio on performance was found to vary depending on fiber length. In mixtures containing 6 and 12 mm fibers, increasing the fiber dosage up to 0.4% improved performance by 15% and 24%, respectively, while in mixtures containing 3 mm fibers, increasing the fiber ratio negatively affected performance. This was attributed to the high surface area/volume ratio of short fibers, their limited bonding capacity with the matrix, and the increased risk of breakage due to over-alignment in the extrusion direction.
- Optimal results in terms of drying-shrinkage performance were obtained with mixtures containing 0.4% 6 mm fibers and 0.2% 3 mm fibers. These mixtures stand out in terms of dimensional stability with their low shrinkage rates.
- The use of 12 mm long fibers negatively impacted performance by 1-33%, unlike other fiber lengths. The intertwining and curling of long fibers caused clumping, creating additional voids within the matrix and reducing shrinkage resistance.
- Using 100% RCA instead of limestone aggregate negatively affected the drying-shrinkage performance by 48-78%. The high water absorption capacity and low rigidity of RCAs were considered the main reasons for this negative effect. Furthermore, it was determined that the use of silica fume also reduced the drying-shrinkage performance of the mixtures by 22%. This is explained by the fact that silica fume, due to its excessive fineness, increases the water requirement.

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DURABILITY and RHEOLOGY PROBLEMS in LIMESTONE CALCINED CLAY CEMENTS (LC3): INCONSISTENCIES BETWEEN LABORATORY DATA and FIELD REALITIES

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ABSTRACT

Limestone calcined clay cement (LC3) has emerged as one of the most promising binder systems within global carbon emission reduction strategies. Despite this rapid industrial acceptance deep engineering inconsistencies exist between current laboratory testing methods and the actual field performance of the material. This study examines the fundamental technical problems inherent in LC3 technology through a current and comprehensive literature synthesis. The research primarily addresses the conflicting findings regarding durability behavior. LC3 systems exhibit superior physical resistance against chloride diffusion by narrowing the critical pore diameter through the formation of carboaluminate phases. On the other hand the carbonation front advances faster compared to conventional concretes due to the lower portlandite reserve. Accelerated carbonation tests in the literature artificially transform this chemical condition into severe degradation by using extremely high gas concentrations and completely ignore the capacity of the matrix to physically stop corrosion through its high electrical resistivity. Another focal point of the study is the production bottleneck. Industrial scale flash calcination applications maximize the amorphous structure and chemical reactivity of the clay. This increased reactivity and the resulting irregular particle morphology significantly increase the water demand of the mixture causing traditional polycarboxylate ether based superplasticizer admixtures to lose their functionality. Current engineering practices attempt to solve this problem merely by altering the timing of admixture addition. This paper demonstrates that in order to truly reflect the potential of LC3 systems in the field there is an urgent need to develop clay specific next generation polymer designs and to establish entirely new performance based standards tailored to exact exposure conditions.

Keywords: Limestone Calcined Clay Cement, Carbonation, Flash Calcination, Rheology, Chloride Resistance.

1. INTRODUCTION

Limestone calcined clay cement (LC3) is an innovative ternary binder system developed to significantly reduce the carbon footprint of the cement industry by lowering clinker consumption. A typical LC3 composition consists of approximately 50% clinker, 30% calcined clay (preferably metakaolin), 15% limestone, and 5% gypsum (Hosen & Chen, 2025; Ijaz et al., 2024; Sharma et al., 2021). The fundamental chemistry of LC3 is based on the interaction between reactive alumina derived from calcined clay and calcium carbonate from limestone, leading to the formation of carboaluminate phases such as monocarboaluminate and hemicarboaluminate. These phases play a critical role in densifying the microstructure and enhancing the overall performance of the system (Dhandapani et al., 2024; Ünverdi & Mardani, 2026).

The development of LC3 technology is primarily driven by the urgent need to decarbonize the cement industry, which is responsible for approximately 5–8% of global greenhouse gas emissions (Koufany et al., 2026; Shao et al., 2025). Traditionally, supplementary cementitious materials (SCMs) such as fly ash and blast furnace slag have been used to reduce clinker content; however, their global availability is rapidly declining, creating a need for alternative binder systems (Hosen & Chen, 2025; Sharma et al., 2021). In contrast, clay and limestone are widely available worldwide, making LC3 a scalable and sustainable solution. It has been reported that LC3 can reduce CO_2 emissions by 30–40%, and in some cases up to 50%, while also requiring lower calcination temperatures, thereby offering significant energy savings (Abir & Mozumder, 2025; Ghazy et al., 2025; Ijaz et al., 2024).

Despite these advantages, one of the most critical technical challenges associated with LC3 systems lies in their fresh-state rheological behavior. The high specific surface area and plate-like morphology of calcined clays significantly increase water demand, yield stress, and plastic viscosity (Muzenda et al., 2020; Nair et al., 2020; J. Zhang et al., 2024). To achieve adequate workability, polycarboxylate ether (PCE)-based superplasticizers are commonly used; however, the rapid adsorption of PCE molecules onto clay surfaces reduces their effectiveness. This interaction results in pronounced slump loss and thixotropic behavior in LC3 mixtures (Ferrari et al., 2025; Kandagaddala et al., 2023; Nair et al., 2020). On the other hand, the inclusion of limestone introduces a filler effect that improves particle packing density and partially compensates for the increased viscosity (Muzenda et al., 2020).

From a durability perspective, LC3 systems exhibit both significant advantages and certain limitations. One of the most distinctive features of LC3 is its superior resistance to chloride ingress. The refinement of pore structure through carboaluminate formation, combined with the chemical and physical binding of chloride ions in the form of Friedel's salt, leads to a substantial reduction in chloride diffusion coefficients compared to ordinary Portland cement (Dhandapani et al., 2018, 2024; Ijaz et al., 2024). Conversely, carbonation behavior remains a critical concern. The reduced clinker content and the continuous consumption of portlandite through pozzolanic reactions decrease the pH buffering capacity of LC3, resulting in faster carbonation front propagation compared to conventional systems (Dhandapani et al., 2024; Sharma et al., 2021). However, the dense microstructure and high electrical resistivity of LC3 limit the ingress of moisture and oxygen, thereby slowing the propagation phase of corrosion even after depassivation (Dhandapani et al., 2024; Ünverdi & Mardani, 2026).

A major issue highlighted in the literature is the inconsistency between laboratory findings and field performance. Accelerated carbonation tests conducted at elevated CO_2 concentrations

(e.g., 1–5%) can artificially degrade hydration products such as C-A-S-H gels and ettringite, leading to an underestimation of the actual carbonation resistance of LC3 systems under natural conditions (Afroz et al., 2023; Ünverdi & Mardani, 2026). Similarly, rapid chloride permeability tests (RCPT), which rely on electrical measurements, may not accurately reflect the true transport properties of LC3 due to differences in pore solution chemistry (Dhandapani et al., 2024). In contrast, field applications in countries such as India and Cuba have demonstrated that LC3 concretes can maintain over 95% of their structural integrity after more than four years under natural exposure conditions (Sharma et al., 2021; Ünverdi & Mardani, 2026).

In recent years, the potential of LC3 systems has extended beyond conventional applications to advanced construction technologies such as 3D concrete printing and engineered cementitious composites (ECC), where their high cohesion can be advantageous (Abir & Mozumder, 2025; Hosen & Chen, 2025). However, for widespread industrial adoption, it is essential to develop next-generation chemical admixtures with higher tolerance to clay minerals and to transition from clinker-based standards to performance-based approaches that better reflect real exposure conditions (Ünverdi & Mardani, 2026).

In this context, the present study aims to provide a comprehensive evaluation of LC3 systems, focusing on the interplay between durability and rheological behavior, and particularly addressing the inconsistencies observed between laboratory data and field performance.

2. FUNDAMENTAL BEHAVIOUR OF LC3 SYSTEMS

2.1. DURABILITY AND RHEOLOGY İN LC3 SYSTEMS

The industrial acceptance of limestone calcined clay cement (LC3) systems is primarily governed by two critical factors: their fresh-state rheological (workability) behavior and their long-term durability performance in the hardened state (Muzenda et al., 2020). Although LC3 systems exhibit a unique microstructural densification due to the synergistic interaction between reactive alumina from calcined clay and calcium carbonate from limestone, the physical characteristics of these components simultaneously introduce significant rheological challenges (Sharma et al., 2021).

One of the most distinctive differences between LC3 systems and conventional ordinary Portland cement (OPC) lies in their fresh-state rheological profile (J. Zhang et al., 2024). The extremely high specific surface area and plate-like (lamellar) morphology of calcined clays, particularly metakaolin, significantly increase water absorption, thereby directly raising the system's water demand, yield stress, and plastic viscosity (Ghazy et al., 2025; Muzenda et al., 2020). To compensate for the increased water demand and to achieve adequate workability, higher dosages of polycarboxylate ether (PCE)-based superplasticizers are required (Nair et al., 2020). However, clay particles tend to rapidly adsorb PCE molecules onto their surfaces or intercalate them within their layered structures, thereby reducing the dispersing efficiency of the admixture and leading to rapid slump loss in LC3 concretes (Ghazy et al., 2025; Ijaz et al., 2024). Figure 1 illustrates the experimental approach used to relate flow loss in LC3 systems to the time-dependent evolution of specific surface area and PCE adsorption, comparing mixtures without flow loss compensation and mixtures in which additional PCE was introduced to restore the initial fluidity (Moghul et al., 2025).

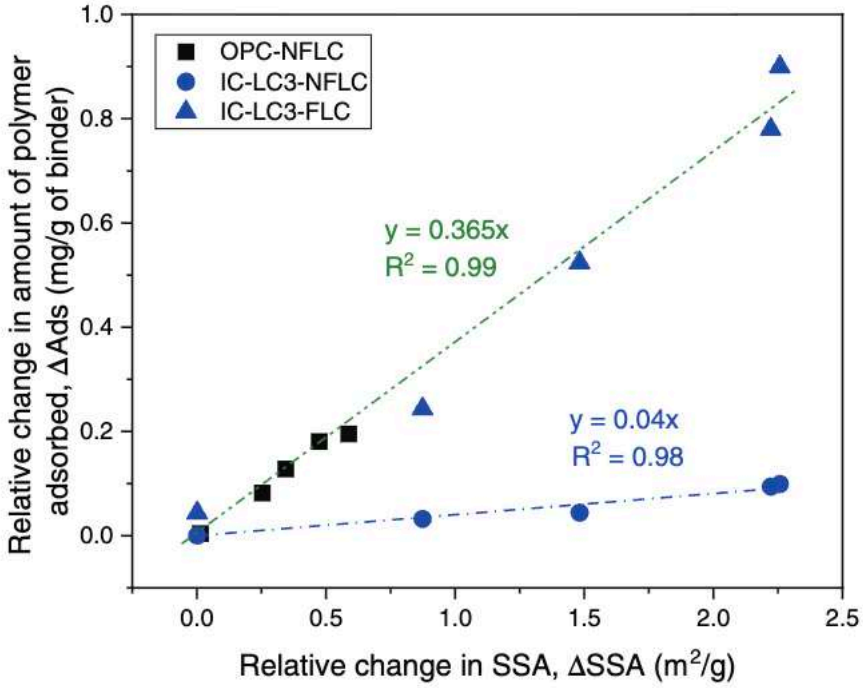


Figure 1. the changes in polymeradsorption and SSA (Moghul et al., 2025)

On the other hand, the inclusion of limestone introduces a filler effect, improving particle packing density and partially compensating for the increased viscosity, thereby contributing positively to flowability (Hosen & Chen, 2025; Muzenda et al., 2020). Furthermore, LC3 pastes exhibit pronounced thixotropic behavior due to the flocculation of clay particles (Ghazy et al., 2025). This thixotropic structure allows the material to become less viscous under shear during pumping, while rapidly rebuilding its structure at rest, thereby maintaining shape stability. This characteristic makes LC3 particularly suitable for advanced construction technologies such as 3D concrete printing (3DCP) (Hosen & Chen, 2025; Ijaz et al., 2024).

The durability performance of LC3 systems is fundamentally linked to the significant refinement of their microstructure (Ghazy et al., 2025). In addition to the formation of calcium aluminosilicate hydrate (C-A-S-H) gels through pozzolanic reactions, the interaction between limestone and reactive alumina leads to the precipitation of hemicarboaluminate and monocarboaluminate phases (Sharma et al., 2021). These phases fill capillary pores, producing a pronounced “space-filling” effect, reducing pore size while significantly increasing the tortuosity of the pore network (Arbab et al., 2025; Ünverdi & Mardani, 2026). Mercury intrusion porosimetry (MIP) results clearly demonstrate that the critical pore diameter in LC3 systems is substantially smaller than that in OPC systems, resulting in a much more impermeable matrix (Figure 2) (Ghazy et al., 2025; Ünverdi & Mardani, 2026).

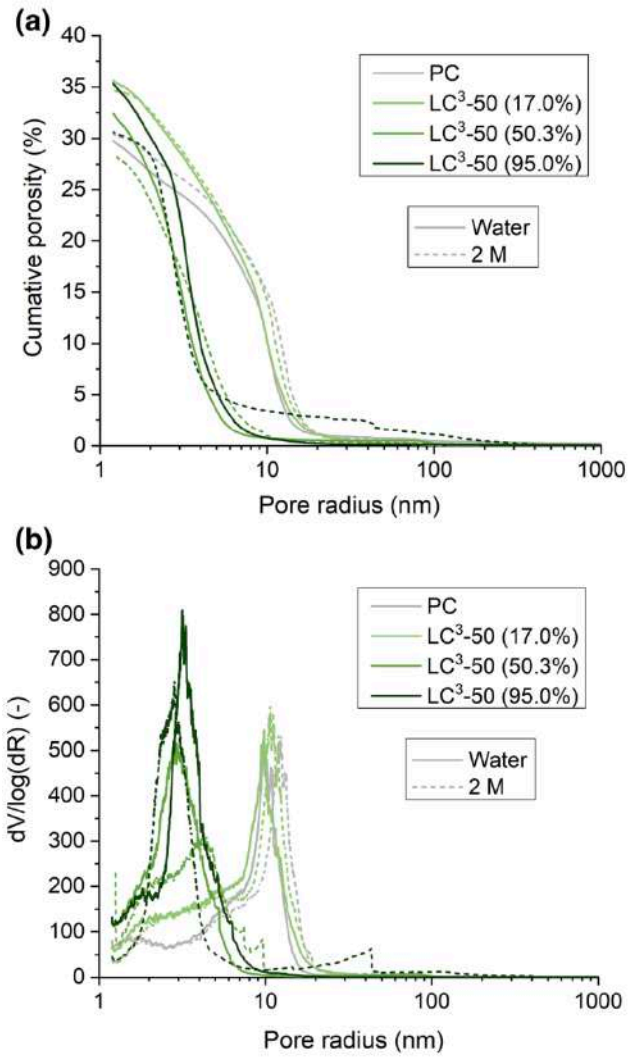


Figure 2. Porosity distribution of PC and LC3-50 (17.0%), (50.3%) and (95.0%) paste samples after 6 m exposure to water or 2 M NaCl solution (Maraghechi et al., 2018)

The most significant outcome of this refined pore structure is the exceptional resistance to chloride ion penetration (Ijaz et al., 2024). The apparent chloride diffusion coefficients of LC3 concretes are reported to be one order of magnitude lower than those of conventional OPC concretes, and in some cases, reductions of up to tenfold have been observed (Shao et al., 2025; Ünverdi & Mardani, 2026). This superior performance is not solely due to the dense microstructure but is also attributed to the chemical binding of chloride ions through the formation of Friedel's salt (Ghazy et al., 2025; Hosen & Chen, 2025)

Similarly, the reduced clinker content and the continuous consumption of portlandite (CH) during pozzolanic reactions enhance the resistance of LC3 systems to sulfate attack (Arbab et al., 2025; Hosen & Chen, 2025). The limited availability of free calcium hydroxide also significantly reduces the risk of alkali–silica reaction (ASR)-induced expansion, in some cases nearly eliminating it compared to OPC systems (Ghazy et al., 2025; Prashar et al., 2026).

Despite these advantages, carbonation behavior remains the primary vulnerability in the durability profile of LC3 systems (Sharma et al., 2021). The significant reduction in clinker content and the consumption of portlandite through pozzolanic reactions decrease the pH buffering capacity of the system, leading to a faster progression of the carbonation front compared to OPC (Ghazy et al., 2025; Marandi & Shirzad, 2025; Shao et al., 2025). However, recent studies emphasize that the advancement

of carbonation depth to the reinforcement level does not necessarily imply immediate corrosion damage (Ünverdi & Mardani, 2026). The highly dense microstructure and elevated electrical resistivity of carbonated LC3 matrices restrict the transport of moisture and oxygen, thereby significantly reducing the corrosion propagation rate (Marandi & Shirzad, 2025; Ünverdi & Mardani, 2026).

Consequently, accelerated carbonation tests conducted under high CO_2 concentrations in laboratory environments may underestimate the actual corrosion resistance of LC3 systems under field conditions, often presenting an overly conservative evaluation of performance (Ünverdi & Mardani, 2026). This discrepancy represents one of the most critical inconsistencies between laboratory data and real-world performance in LC3 systems.

2.2. RHEOLOGICAL PROPERTIES AND WATER DEMAND

One of the most prominent technical challenges limiting the widespread industrial adoption of limestone calcined clay cement (LC3) systems is their fresh-state rheological behavior and increased water demand. Compared to conventional ordinary Portland cement (OPC), LC3 exhibits a significantly different workability profile due to the physical and chemical nature of its constituent materials (Muzenda et al., 2020). These differences primarily stem from the unique characteristics of calcined clay, particularly metakaolin, which plays a dominant role in governing fresh-state behavior.

The increased water demand in LC3 systems is mainly attributed to the extremely high specific surface area and the plate-like (lamellar) or sponge-like morphology of calcined clays (Ghazy et al., 2025; Nair et al., 2020). This structural nature leads to rapid adsorption of water by clay particles within the fresh paste. Recent studies employing advanced water characterization techniques, such as Differential Scanning Calorimetry (DSC) and Time Domain Nuclear Magnetic Resonance (TD-NMR), have clearly demonstrated that calcined clay rapidly consumes the free (unbound) water present in fresh mixtures. The rapid reduction of free water directly decreases the flowability of the mixture and effectively lowers the water-to-binder ratio, thereby significantly restricting workability (Ferrari et al., 2025).

In addition to increasing water demand, higher calcined clay content has a pronounced impact on the rheological parameters of fresh LC3 mixtures. Specifically, both static and dynamic yield stress, plastic viscosity, and cohesion increase significantly with increasing clay content (Muzenda et al., 2020; J. Zhang et al., 2024). This behavior is mainly governed by the negative surface charge of clay particles and their tendency to flocculate. As a result, LC3 pastes exhibit highly pronounced thixotropic behavior, characterized by structural build-up at rest and flow under shear stress (Ghazy et al., 2025; Muzenda et al., 2020). While increased viscosity and cohesion can lead to pumping difficulties and rapid slump loss in conventional concrete applications, these same characteristics can be advantageous in layer-by-layer construction processes. In particular, the ability of the material to retain its shape after deposition, known as buildability, makes LC3 an excellent candidate for advanced technologies such as 3D concrete printing (3DCP) (Ghazy et al., 2025; Hosen & Chen, 2025; Kandagaddala et al., 2023).

In contrast to calcined clay, limestone plays a beneficial role in modifying the rheological behavior of LC3 systems. Limestone particles typically exhibit a more spheroidal morphology, which induces a “ball-bearing” effect within the paste, reducing internal friction (Muzenda et al., 2020; J. Zhang et al., 2024). This physical filler effect improves particle packing density and partially offsets the increase in yield stress and viscosity caused by calcined clay, thereby enhancing the flowability of LC3 mixtures (Ghazy et al., 2025; J. Zhang et al., 2024). However, this beneficial effect is highly dependent on particle morphology; the use of acicular (needle-like) aggregates, such as wollastonite, has been reported to increase viscosity instead of improving flowability (J. Zhang et al., 2024).

To manage the increased water demand while maintaining a low water-to-binder (w/b) ratio for optimal mechanical and durability performance, the use of polycarboxylate ether (PCE)-based superplasticizers is essential in LC3 systems (Ghazy et al., 2025; Nair et al., 2020). Studies have shown

that PCE-based admixtures provide better dispersion efficiency in LC3 systems compared to lignosulfonate or sulfonated naphthalene formaldehyde (SNF)-based admixtures (Kandagaddala et al., 2023; Nair et al., 2020). Nevertheless, the surface chemistry of calcined clay significantly limits the effectiveness of these admixtures. Clay particles tend to rapidly adsorb PCE molecules or trap them within their layered structure, preventing the superplasticizer from effectively dispersing cement particles (Ijaz et al., 2024; Nair et al., 2020).As a consequence, significantly higher dosages of superplasticizer are required compared to OPC systems, and substantial slump loss is often observed within the first few hours after mixing (Ghazy et al., 2025; Nair et al., 2020).

To overcome these rheological challenges, several strategies have been proposed in recent studies. These include the delayed addition of superplasticizers, the development of next-generation PCE molecules with higher clay tolerance and optimized side-chain density, and the adjustment of sulfate balance within the system (Ghazy et al., 2025; Ijaz et al., 2024). Such approaches aim to improve the workability of LC3 systems and enhance their feasibility for large-scale industrial applications.

3. DURABILITY PERFORMANCE OF LC3 SYSTEMS

3.1. CHLORIDE RESISTANCE

One of the most prominent and widely acknowledged durability advantages of limestone calcined clay cement (LC3) systems is their exceptional resistance to chloride ion penetration (Dhandapani et al., 2018; Ghazy et al., 2025). Both laboratory investigations and field studies have consistently shown that the apparent chloride diffusion and migration coefficients obtained from LC3 concretes are generally one order of magnitude lower—and in some cases up to ten times lower—than those measured in equivalent concretes produced with ordinary Portland cement (OPC) (Dhandapani & Santhanam, 2020; Ünverdi & Mardani, 2026). This outstanding performance arises from the simultaneous and synergistic contribution of chemical binding capacity and the physical refinement of the microstructure .

A primary mechanism underlying the enhanced chloride resistance is the significant refinement of the pore structure. In LC3 systems, in addition to the formation of C-A-S-H gels, the reaction between reactive alumina derived from calcined clay and carbonate ions from limestone leads to the extensive precipitation of monocarboaluminate and hemicarboaluminate phases (Maraghechi et al., 2018; Sharma et al., 2021; Ünverdi & Mardani, 2026). These phases exert a pronounced space-filling effect, densifying the matrix, dramatically reducing the critical pore diameter—often to below 10 nm—and increasing the tortuosity of the pore network (Dhandapani & Santhanam, 2020; Ünverdi & Mardani, 2026). This highly tortuous and labyrinth-like microstructure physically impedes the diffusion of chloride ions, thereby significantly limiting their transport rate.

In addition to physical refinement, the chemical binding capacity of LC3 systems plays a crucial role in chloride resistance. The high alumina content provided by calcined clay promotes the formation of AFm phases, which enable the chemical binding of chloride ions in the form of Friedel's salt (Dhandapani et al., 2024; Ijaz et al., 2024). However, recent studies have revealed important time-dependent nuances in this mechanism. LC3 pastes reach their maximum chemical chloride binding capacity very rapidly, typically within the first 14 days, due to the early formation of carboaluminate phases (Ünverdi & Mardani, 2026). At later ages, such as up to 56 days of hydration, OPC systems may eventually match or even exceed LC3 in terms of total chloride binding capacity. Nevertheless, the superior long-term chloride resistance of LC3 is not primarily attributed to an indefinitely increasing chemical binding capacity, but rather to the sustained suppression of ion transport resulting from the refined pore structure (Ünverdi & Mardani, 2026).

Another critical aspect in evaluating chloride resistance in LC3 systems is the limitation of commonly used accelerated laboratory test methods. The Rapid Chloride Permeability Test (RCPT – ASTM C1202), widely adopted in industry, is based on electrical conductivity and is therefore highly sensitive not only to the pore structure but also to the chemistry of the pore solution (Abdulqader et al.,

2023; Dhandapani et al., 2018). In LC3 systems, the pozzolanic reactions of calcined clay bind alkalis in the pore solution, significantly reducing its pH and electrical conductivity (Dhandapani et al., 2024). As a result, the measured charge passed in RCPT tests is artificially lowered, giving the impression of an extremely low permeability that may overestimate the actual resistance to chloride ingress under field conditions (Ünverdi & Mardani, 2026). Therefore, for accurate service life predictions and realistic performance assessment, it is recommended to rely on long-term natural chloride diffusion tests, such as ASTM C1556, which are less influenced by pore solution chemistry (Dhandapani et al., 2024; Ünverdi & Mardani, 2026).

From a sustainability and practical application perspective, one of the most encouraging findings is that high chloride resistance in LC3 systems does not necessarily require high-purity calcined clays. Studies have shown that even low-quality clays with kaolinite contents as low as 17% can produce LC3 concretes with chloride migration coefficients at least 50% lower than those of conventional OPC concretes (Dhandapani et al., 2024; Ünverdi & Mardani, 2026). Furthermore, pilot field studies involving exposure to natural seawater conditions over approximately 18 months have demonstrated that LC3 concretes maintain chloride concentrations at a depth of 20 mm that are approximately seven times lower than those measured in OPC concretes (Dhandapani et al., 2024).These findings strongly confirm that LC3 systems are highly reliable binders for mitigating reinforcement corrosion in aggressive chloride environments and for significantly extending the service life of concrete structures under real field conditions.

3.2. CARBONATION BEHAVIOUR

Carbonation resistance is one of the most debated aspects of the durability profile of limestone calcined clay cement (LC3) systems and is often regarded as the weakest link or most vulnerable parameter of the material (Sharma et al., 2021; Ünverdi & Mardani, 2026). Compared to conventional ordinary Portland cement (OPC), the carbonation front in LC3 matrices tends to progress more rapidly. However, this behavior is frequently misinterpreted and attributed solely to permeability-related factors. In reality, carbonation in LC3 systems is governed primarily by the reduction in chemical alkaline reserve rather than by physical transport properties (Prashar et al., 2026; Sharma et al., 2021).

The accelerated carbonation observed in LC3 systems is mainly a consequence of the reduced alkaline buffering capacity of the material. The approximately 50% reduction in clinker content, combined with the continuous consumption of calcium hydroxide (portlandite, CH) through pozzolanic reactions of calcined clay from early ages, significantly decreases the system's ability to maintain a high pH (Abir & Mozumder, 2025; Hosen & Chen, 2025). As a result, the matrix has a diminished capacity to neutralize carbon dioxide penetrating from the environment, allowing the carbonation front to penetrate deeper compared to OPC or single supplementary cementitious material (SCM) systems such as fly ash or slag (Ghazy et al., 2025; Ijaz et al., 2024).

Beyond its chemical implications, carbonation in LC3 systems also induces notable microstructural transformations. The carbonation of aluminate phases and ettringite can lead to a reduction in solid volume and the release of bound water (Sharma et al., 2021). While this process may potentially coarsen the critical pore structure, LC3-specific mechanisms can partially mitigate these effects. In particular, the hemicarboaluminate (Hc) phase reacts with atmospheric CO_2 and transforms into monocarboaluminate (Mc), effectively acting as a "carbonation sink" within the system (Ghazy et al., 2025; Ijaz et al., 2024). Despite structural degradation and volumetric changes such as shrinkage associated with ettringite decomposition, the overall porosity in carbonated LC3 regions can remain relatively stable, and in some cases, additional densification of the matrix may occur (Ünverdi & Mardani, 2026).Indeed, experimental findings indicate that the sorptivity values of carbonated LC3 concretes are lower than those of carbonated OPC concretes (Sharma et al., 2021).

A key conceptual distinction in evaluating carbonation performance in LC3 systems lies in differentiating between corrosion initiation and corrosion propagation. Although the carbonation front may reach the reinforcement more rapidly in LC3 systems, resulting in a shorter corrosion initiation

period, this does not necessarily translate into immediate structural damage (Prashar et al., 2026; Ünverdi & Mardani, 2026). Even when the passive layer is destabilized due to reduced pH, the progression of corrosion requires the transport of oxygen and moisture. However, the highly refined pore structure and elevated electrical resistivity of carbonated LC3 matrices significantly restrict ionic and moisture transport (Figure 3) (Prashar et al., 2026; Sharma et al., 2021). This physical limitation effectively suppresses corrosion propagation currents, in some cases reducing corrosion rates to negligible levels. Consequently, when evaluated in terms of total service life, LC3 systems can compete with or even outperform OPC under certain conditions (Ünverdi & Mardani, 2026).

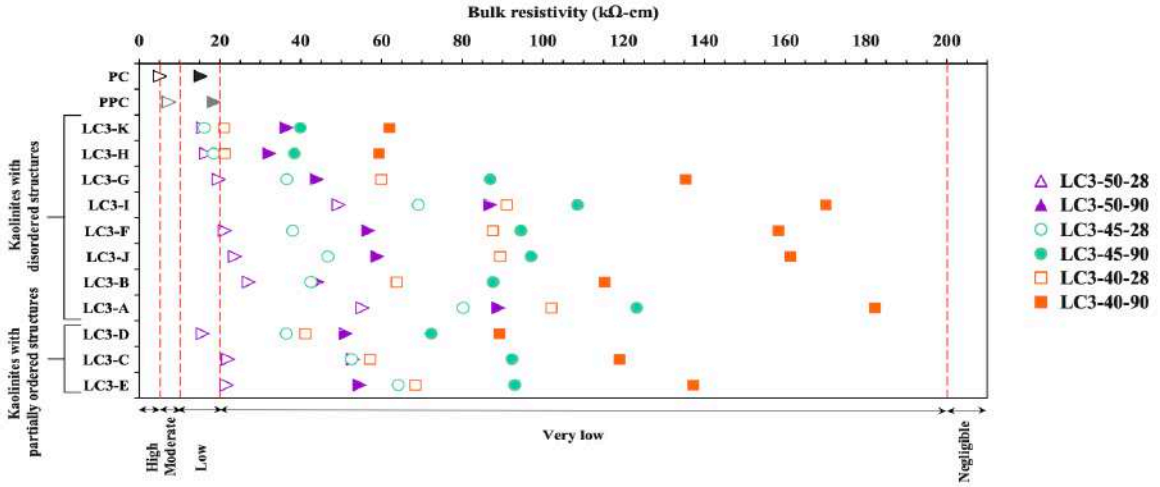


Figure 3. The bulk resistivity of PC anf LC3 samples (Arbab et al., 2025)

A major source of the pessimistic perception regarding LC3 carbonation resistance in the literature stems from the use of aggressive accelerated carbonation tests conducted under unrealistically high CO_2 concentrations, typically in the range of 4–5% (Ünverdi & Mardani, 2026). These extreme conditions can artificially degrade hydration products such as C-A-S-H gels and ettringite, forcing deterioration mechanisms that do not occur under natural exposure conditions. As a result, LC3 systems are often unfairly penalized in laboratory evaluations. For more realistic durability assessment, carbonation testing should be conducted under lower CO_2 concentrations (e.g., ≤1%) or through natural exposure studies (Ünverdi & Mardani, 2026).

In addition, carbonation may introduce additional risks in chloride-rich environments, such as marine exposure conditions. As carbonation progresses and pH decreases, chloride ions previously bound within Friedel's salt or gel structures may be released back into the pore solution as free chlorides, potentially accelerating corrosion processes (Dhandapani et al., 2024). In such coupled attack scenarios involving both carbonation and chloride exposure, the incorporation of advanced nanomaterials such as nanosilica (NS) or graphene oxide (GO) has been shown to significantly enhance performance. Studies indicate that these nanomaterials can reduce carbonation depth by more than 50% and improve the interfacial transition zone (ITZ), thereby strengthening the overall durability of LC3 systems (Abir & Mozumder, 2025).

4. LABORATORY–FIELD DISCREPANCIES AND PRACTICAL IMPLICATIONS

4.1. LC3 LABORATORY AND FIELD STUDIES

Limestone calcined clay cement (LC3) has evolved from a laboratory-scale innovation into one of the most promising binder systems integrated into large-scale industrial applications in line with the global decarbonization goals of the cement industry (Ünverdi & Mardani, 2026). The successful transfer of its superior mechanical and durability performance observed under laboratory conditions to real field

environments and industrial-scale production represents a critical intersection between material science and structural engineering (Ünverdi & Mardani, 2026).

Controlled laboratory studies have demonstrated that LC3 systems can match or even outperform conventional ordinary Portland cement (OPC) in terms of chloride and sulfate resistance, as well as early-age strength development (Hosen & Chen, 2025). To facilitate quality control and accelerate material characterization, laboratory standards such as the R3 test (ASTM C1897) have been developed to rapidly and reliably assess the pozzolanic reactivity of calcined clays (Hosen & Chen, 2025; Ünverdi & Mardani, 2026). However, the literature clearly indicates that commonly used accelerated laboratory durability tests introduce significant biases when applied to LC3 systems (Ünverdi & Mardani, 2026). For instance, the Rapid Chloride Permeability Test (RCPT – ASTM C1202), which relies on electrical conductivity, can overestimate the impermeability of LC3 due to its lower pore solution alkalinity and higher electrical resistivity, thereby presenting an artificially enhanced performance (Dhandapani et al., 2024; Ünverdi & Mardani, 2026). Similarly, accelerated carbonation tests conducted at elevated CO_2 concentrations (e.g., 4–5%) can induce artificial degradation of C-A-S-H gels and ettringite within the LC3 matrix, leading to an unfairly pessimistic estimation of long-term performance. These findings highlight the necessity of shifting from accelerated laboratory models toward long-term natural diffusion tests and field exposure data for more realistic performance evaluation (Ünverdi & Mardani, 2026).

One of the key advantages facilitating the industrial adoption of LC3 technology is its compatibility with existing cement production infrastructure. LC3 can be produced with minor modifications to current plants, without requiring substantial capital investment in new facilities (Shao et al., 2025). The calcination of clay occurs at significantly lower temperatures (700–850 °C) compared to clinker production, allowing the use of idle rotary kilns or modern flash calciners for efficient large-scale production, while these two have different morphology (Figure 4). Today, countries such as Colombia, Côte d'Ivoire, and Ghana are producing hundreds of thousands of tons of LC3 annually using flash calcination technologies (Ünverdi & Mardani, 2026). Furthermore, one of the most critical findings from industrial trials and field applications is that transitioning from OPC to LC3 does not require retraining of construction workers or recalibration of existing equipment (Hosen & Chen, 2025; S. S. Reddy & Reddy, 2021).

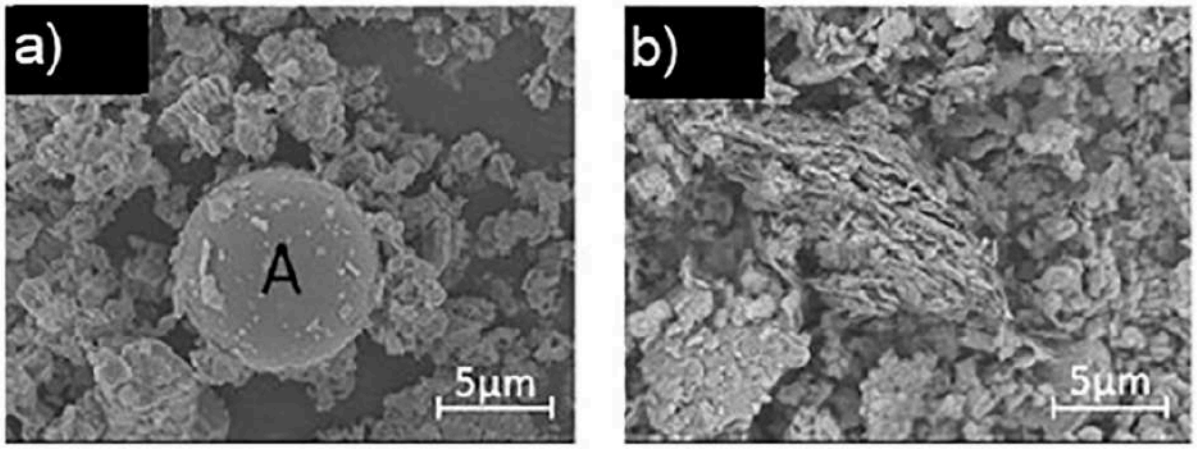


Figure 4. Secondary electron images of metakaolins calcined by a) flash calcination, b) rotary kiln calcination (Khalifa et al., 2020; San Nicolas et al., 2013)

Field performance studies provide essential validation of LC3 behavior under real environmental conditions. Pilot applications, particularly in Cuba and India, have demonstrated that LC3-based concretes maintain high structural integrity across a range of climatic conditions (S. S. Reddy & Reddy, 2021). In India, LC3 has been successfully used in the construction of check dams in Orchha, pavements, concrete paving blocks, and autoclaved aerated concrete (AAC) blocks and multi-storey buildings in the Swiss Embassy complex in New Delhi (S. S. Reddy & Reddy, 2021; Shao et al., 2025).

Long-term field exposure studies under marine conditions further confirm the superior durability of LC3 systems. At the Punta Matamoros marine exposure site in Cuba, LC3 concrete blocks subjected to natural chloride and sulfate exposure for approximately 18 months exhibited chloride penetration depths and concentrations about 2.7 times lower than those measured in OPC concretes (Dhandapani et al., 2024). Similarly, in India, field structures and breakwater tetrapods constructed with LC3 approximately 400 meters from the coastline showed extremely low chloride migration coefficients ($< 1 \times 10^{-12}$ m²/s) after one year of exposure (Dhandapani et al., 2024). These field validations strongly demonstrate that LC3 systems can maintain more than 95% structural integrity over service periods exceeding four years, even under aggressive environmental conditions (Shao et al., 2025)

In conclusion, the transition of LC3 from laboratory innovation to field implementation has clearly demonstrated its technical feasibility and robustness (Ghazy et al., 2025). However, for its widespread global adoption, existing concrete standards must be reconsidered. Traditional prescriptive specifications based on clinker content or 28-day compressive strength should be replaced by performance-based standards that account for real exposure conditions. Such a transition is essential for unlocking the full potential of LC3 systems as a sustainable solution for future construction (Ünverdi & Mardani, 2026).

4.2. LABORATORY TEST METHODS AND THEIR LIMITATIONS

The development of low-clinker innovative binders such as limestone calcined clay cement (LC3) has clearly exposed the limitations and inadequacies of existing laboratory test standards originally designed for conventional ordinary Portland cement (OPC) systems (Ünverdi & Mardani, 2026). A growing body of literature indicates that, due to the distinct reaction kinetics and unique microstructural evolution of LC3, many traditional accelerated testing methods can produce biased and potentially misleading results when applied to these systems (Dhandapani et al., 2024; Ünverdi & Mardani, 2026).

Conventionally, the pozzolanic activity of supplementary materials has been evaluated using methods such as the Strength Activity Index (SAI), which require extended testing durations ranging from 28 to 90 days, rendering them impractical for quality control purposes (Koufany et al., 2026). To overcome this limitation, the R3 (Rapid, Relevant, and Reliable) test has been developed and standardized as ASTM C1897, providing a rapid and reliable approach to assess the pozzolanic reactivity of calcined clays and other supplementary cementitious materials (SCMs) (Avet et al., 2016; Koufany et al., 2026). By employing isothermal calorimetry and bound water measurements, the R3 method can deliver meaningful reactivity data in less than seven days. However, a key limitation of this method is its inability to directly evaluate mechanical strength or long-term durability performance (Hosen & Chen, 2025).

The Rapid Chloride Permeability Test (RCPT – ASTM C1202), widely used in industry to assess chloride resistance, also presents significant limitations when applied to LC3 systems (Dhandapani et al., 2024). As an electrical conductivity-based test, RCPT reflects not only the physical permeability of the matrix but also the chemistry of the pore solution. In LC3 systems, the pozzolanic reactions of calcined clay consume portlandite and bind alkalis (Na^+ and K^+), significantly reducing the ionic concentration and electrical conductivity of the pore solution (Dhandapani et al., 2024; Dhandapani & Santhanam, 2020). Consequently, the measured charge passed in RCPT tests is artificially lowered, leading to an overestimation of chloride resistance compared to actual field performance (Ünverdi & Mardani, 2026). To address this limitation, researchers have proposed alternative approaches such as the “Formation Factor,” which minimizes the influence of pore solution chemistry, or the use of long-term natural chloride diffusion tests (e.g., ASTM C1556), which, although requiring more than 35 days, provide results that more accurately reflect real service conditions (Dhandapani et al., 2024; Dhandapani & Santhanam, 2020).

Similarly, accelerated carbonation tests conducted in laboratory environments introduce considerable uncertainties when evaluating LC3 systems. These tests typically involve elevated CO_2

concentrations ranging from 1% to 5%, which do not represent natural exposure conditions (Shao et al., 2025).Such aggressive environments can artificially degrade hydration products, including calcium aluminosilicate hydrate (C-A-S-H) gels and ettringite, forcing deterioration mechanisms that would not occur under realistic conditions (Ünverdi & Mardani, 2026).In addition, high CO_2 levels may induce rapid pore clogging effects, masking the actual carbonation mechanisms occurring under natural conditions (Shao et al., 2025).Therefore, for realistic service life prediction, it is essential to limit CO_2 concentrations to a maximum of 1% in accelerated tests and to calibrate laboratory findings with long-term natural exposure data (Ünverdi & Mardani, 2026).

A similar issue arises in sulfate resistance testing. Laboratory tests often utilize magnesium sulfate ($MgSO_4$) solutions to accelerate sulfate attack; however, these conditions are significantly more severe than those encountered in real field environments. As a result, the degradation mechanisms observed in such tests may not accurately represent the actual sulfate resistance of LC3 systems, and the interpretation of these results must be approached with caution (Hosen & Chen, 2025; Sharma et al., 2021) (Sharma et al., 2021; Hosen & Chen, 2025).

Ultimately, current concrete standards and specifications are largely prescriptive in nature, relying heavily on parameters such as 28-day compressive strength and clinker content as universal indicators of durability. However, the durability of LC3 systems is primarily governed by microstructural features, particularly pore refinement and increased tortuosity, rather than absolute strength values. Consequently, the direct application of conventional strength-based specifications to LC3 and similar multi-component binder systems may significantly underestimate their true performance potential under aggressive exposure conditions (Ünverdi & Mardani, 2026)

4.3. FIELD PERFORMANCE AND REAL-WORLD CONDITIONS

One of the most compelling strengths of limestone calcined clay cement (LC3) technology is its ability to successfully translate laboratory-scale performance into large-scale field applications and real-world conditions. One of the most critical findings from industrial field implementations is that transitioning from conventional ordinary Portland cement (OPC) to LC3 does not require retraining of the existing workforce or recalibration of construction equipment (S. S. Reddy & Reddy, 2021). This observation directly demonstrates the practical applicability and workability of LC3 systems under real construction conditions.

Globally, LC3 has been successfully implemented in more than twenty large-scale projects, particularly in developing countries (Shao et al., 2025). In India, LC3 has been used as the primary binder in the construction of check dams in the Orchha region, concrete paving blocks, and autoclaved aerated concrete (AAC) block walls and two-storey buildings within the Swiss Embassy complex in New Delhi (Ijaz et al., 2024; S. S. Reddy & Reddy, 2021). Furthermore, in the Bharatmala Highway Project in India, the use of non-kaolinitic clays, such as montmorillonite calcined at temperatures above 800 °C, has enabled the overcoming of raw material limitations. This adaptation has resulted in an annual reduction of approximately 15 million tons of CO2 emissions (Shao et al., 2025). Similarly, in Colombia, hundreds of thousands of tons of LC3 are commercially produced annually for use in major infrastructure projects such as bridges and high-rise buildings, while in countries such as Côte d'Ivoire and Ghana, local clays are processed at an industrial scale using flash calcination technologies (Ünverdi & Mardani, 2026)

Field exposure studies provide some of the most convincing evidence of LC3 performance, particularly in terms of chloride resistance. Data obtained under real environmental conditions confirm that the superior resistance to chloride ingress observed in laboratory studies is consistently replicated in the field (Dhandapani et al., 2024). At the Punta Matamoros (ECOT) marine exposure site in Cuba, LC3-50 concrete blocks subjected to wave action and salt spray were monitored over a period of 18–24 months. The results indicated that chloride concentrations measured at a depth of 20 mm were approximately seven times lower than those observed in conventional OPC concretes (Dhandapani et

al., 2024). Similarly, in India, full-scale breakwater tetrapods produced using Portland Pozzolana Cement (PPC) partially replaced by 30% calcined clay–limestone (LC2) were deployed in coastal environments (Dhandapani et al., 2024). These tetrapods, along with field-aged test columns, exhibited extremely low chloride migration coefficients—below 1×10^{-12} m²/s—after one year of exposure under harsh marine conditions, thereby confirming the structural reliability of LC3 in coastal infrastructure applications (Dhandapani et al., 2024).

Long-term field validation studies conducted in India, Cuba, and other regions have demonstrated that structures built with LC3 maintain more than 95% structural integrity under severe service conditions over periods exceeding four years (Shao et al., 2025). The formation of carboaluminate phases within the matrix effectively binds free chloride ions, which significantly extends maintenance and repair intervals in reinforced concrete structures, particularly in coastal environments—from approximately 15 years in conventional systems to up to 25 years in LC3-based systems (Shao et al., 2025). Although the initial investment required for LC3 production may be slightly higher, typically by 5–10% compared to traditional systems, its superior resistance to coupled degradation mechanisms such as chloride ingress and carbonation can reduce total lifecycle costs by up to 30%. This makes LC3 a highly competitive and sustainable solution for long-term infrastructure performance (Shao et al., 2025).

4.4. EVALUATION OF CURRENT ENGINEERING APPLICATIONS

Limestone calcined clay cement (LC3), owing to its unique rheological behavior and chemically refined microstructure, has extended far beyond conventional concrete applications and is now driving innovation in a wide range of advanced engineering technologies that support sustainability (Ijaz et al., 2024). This multifaceted performance positions LC3 not merely as an alternative binder, but as a key enabler of next-generation engineering solutions.

One of the most promising application areas of LC3 systems is 3D concrete printing (3DCP) technologies. In extrusion-based manufacturing processes, the fresh-state rheological behavior of the material is of critical importance. In this context, the presence of calcined clay particles—particularly metakaolin—with high specific surface area and plate-like morphology induces pronounced thixotropic behavior and high static yield stress in LC3 systems (Beigh et al., 2020). Unlike conventional ordinary Portland cement (OPC), LC3 exhibits strong shape retention and layer stability, which effectively prevent the collapse of freshly deposited layers during the printing process (Long et al., 2021). Experimental studies have confirmed that optimized LC3 mixtures outperform OPC in terms of extrudability and buildability, while significantly reducing the carbon footprint of 3D printing technologies, thereby enhancing their sustainability (Chen et al., 2019).

Another important application domain of LC3 is in high-performance cementitious composites. Engineering Cementitious Composites (ECC), which typically require high binder contents, are associated with elevated CO_2 emissions and significant shrinkage issues. These limitations can be effectively mitigated through the incorporation of LC3 (Yu et al., 2020). LC3-based ECC systems reinforced with polypropylene (PP) or polyvinyl alcohol (PVA) fibers exhibit comparable or superior performance to OPC-based systems in terms of multiple cracking behavior, high ductility, and crack width control, typically maintaining crack widths below 30 μm (D. Zhang et al., 2020; Zhu et al., 2021). Furthermore, when used as the primary binder in High-Strength Strain-Hardening Cementitious Composites (HS-SHCC), LC3 can provide mechanical strength and energy absorption capacity (toughness) comparable to conventional systems, offering a low-carbon alternative for infrastructure subjected to dynamic loads such as seismic actions (Wang et al., 2021).

LC3 systems also demonstrate significant potential in the context of recycled aggregate utilization and nanotechnological optimization. In the management of construction and demolition (C&D) waste, recycled brick aggregates (RBA), which typically suffer from high water absorption and weak interfacial transition zones (ITZ), can be effectively improved through the use of LC3 binders (Guo et al., 2022). Recent experimental studies have shown that when LC3 systems are synergistically modified with advanced nanomaterials such as nanosilica (NS) and graphene oxide (GO)—for example, at optimal

dosages of 2.5% NS and 0.04% GO—the microstructure surrounding recycled aggregates becomes significantly densified, and the ITZ is substantially strengthened (Abir & Mozumder, 2025). Through such nanomodification strategies, LC3 concretes incorporating 100% untreated RBA have achieved compressive strengths of up to 41.5 MPa at 180 days, while reducing chloride migration by up to 64% compared to OPC systems (Abir & Mozumder, 2025). These findings highlight the potential of LC3 systems to play a transformative role in sustainable concrete technologies and circular economy practices.

Beyond structural applications, LC3 also offers considerable advantages in geotechnical engineering. It has been demonstrated as an effective and environmentally friendly alternative to OPC in the stabilization of weak and expansive soils (Ijaz et al., 2024). The improved performance in soil stabilization is attributed to the formation of ettringite phases, which fill voids within the soil matrix and significantly reduce permeability (Ijaz et al., 2024). In addition, LC3 systems have proven effective in the remediation of heavy metal-contaminated soils. Hazardous metals such as zinc and lead can be immobilized within the calcium aluminosilicate matrix, thereby reducing leaching rates to levels well below environmental safety thresholds (V. A. Reddy et al., 2019).

5. CONCLUSIONS

This study highlights the fundamental differences of LC3 systems compared to conventional binders and emphasizes the critical factors governing their real-world performance.

- LC3 systems represent a fundamentally different binder compared to OPC, where performance is governed by the interaction between microstructural refinement, chemical reactions, and rheological behavior.
- From a rheological perspective, the high specific surface area and layered structure of calcined clays significantly increase water demand, yield stress, and viscosity, while also inducing strong thixotropic behavior. Although this creates challenges in conventional applications, it provides major advantages for emerging technologies such as 3D concrete printing.
- LC3 systems exhibit outstanding chloride resistance due to combined pore refinement and chemical binding mechanisms, resulting in significantly lower chloride diffusion compared to OPC.
- Carbonation remains the most critical limitation of LC3, primarily due to reduced alkaline buffering capacity. However, the dense microstructure and high electrical resistivity significantly limit corrosion propagation, creating a “carbonation–corrosion paradox”.
- A major inconsistency exists between laboratory results and field performance. Accelerated tests such as RCPT and high CO_2 carbonation can produce misleading results, whereas field studies confirm that LC3 maintains high durability and structural integrity under real conditions.
- LC3 has demonstrated strong applicability in advanced engineering fields, including 3D printing, ECC systems, recycled aggregate concrete, and geotechnical stabilization, supporting both sustainability and performance.
- The compatibility of LC3 with existing cement production infrastructure significantly facilitates its industrial adoption without major operational changes.
- Current prescriptive standards based on compressive strength and clinker content are insufficient for evaluating LC3 performance, highlighting the need for performance-based design approaches.

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EFFECTS OF MOLECULAR CHAIN RATIO OF PCE-BASED GRINDING AIDS ON FLOWABILITY OF CEMENTITIOUS SYSTEM

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ABSTRACT

Polycarboxylate-based water-reducing admixtures (PCEs) can be synthesized with tailored molecular structures to achieve specific performance objectives, such as enhancing the initial flowability or improving the workability retention. This design flexibility, derived from their comb-like molecular structure, is a key characteristic that distinguishes PCEs from conventional ones. The similarity between the adsorption mechanisms of PCEs and those of traditional grinding aids (GAs) has prompted interest in employing PCEs as alternative GAs during clinker grinding. The underlying rationale is that PCEs can potentially improve grinding efficiency while enhancing the flowability of the resulting cementitious systems simultaneously. However, the influence of the PCE molecular structure, particularly parameters critical to grinding efficiency, on the subsequent flowability of cementitious systems remains insufficiently explored. In this context, the present study synthesizes two PCE-type GAs with identical main-chain lengths, side-chain lengths, densities, and pH values, but with different side-chain-to-main-chain ratios (14 and 27) and molecular weights. Seven Portland cements were produced, including a control cement without GA, and were prepared by intergrinding the clinker with the synthesized PCE-type GAs at three dosages (0.025%, 0.05%, and 0.1% by feed weight). The time-dependent flow performance of mortar mixtures produced with these cements was evaluated. The results indicate that the initial flowability of mortars prepared with cement ground using 0.025% PCE with a low side-chain/main-chain ratio (14) was improved relative to the control. Conversely, mortars produced with cement containing the same PCE dosage but a higher ratio (27) exhibited reduced initial flowability. The consistency retention of mixtures prepared with PCEs of different structural ratios showed no significant difference from that of the control. In conclusion, the use of PCE-type GAs with a low side-chain/main-chain ratio (14) at a low dosage (0.025%) enhances the initial flow performance of cementitious systems.

Keywords: PCE-based grinding aids, side chain/main chain ratio, initial flow performance, time-dependent flow

1. INTRODUCTION

Polycarboxylate-based water-reducing admixtures (PCEs) represent a key class of chemical admixtures in modern cement and concrete technology due to their ability to significantly enhance workability at a constant water-to-cement (w/c) ratio while maintaining cost efficiency (Lei et al., 2022; Kobya et al., 2023a; Ma et al., 2022). Their comb-like molecular architecture consists of an anionic backbone that adsorbs onto cement particle surfaces via electrostatic interactions and polyethylene glycol (PEG) side chains that generate steric repulsion, thereby preventing particle agglomeration (Flatt & Schober, 2012; Sha et al., 2020; Xiang et al., 2020; Kobya et al., 2023b). Adsorption is primarily governed by the density and distribution of carboxylate groups, whereas dispersion efficiency depends on side-chain length, density, and flexibility (Flatt et al., 2009; Erzengin et al., 2018). At low w/c ratios, excess non-adsorbed PCE molecules may also contribute to lubrication within the system (Lange & Plank, 2016; Nawa et al., 2000). Owing to the tunability of their molecular structure, global PCE production has exceeded 10 million tons annually (Ma et al., 2022; Kobya et al., 2023b).

Beyond their conventional use as superplasticizers, PCEs have recently attracted attention as potential grinding aids (GAs) in clinker comminution (He et al., 2021; Dengiz et al., 2022; Kaya et al., 2025; Çinku et al., 2025). Grinding efficiency is strongly influenced by both material-related parameters—such as mineralogical composition, hardness, and particle size distribution—and operational variables including mill speed, grinding media characteristics, and filling ratio (Wang et al., 2023a; Kaya et al., 2024b). During clinker grinding, the generation of fresh fracture surfaces produces oppositely charged sites that promote agglomeration and adhesion to grinding media through electrostatic and van der Waals forces, thereby decreasing milling efficiency (Benzer et al., 2001; Zhang et al., 2015).

Conventional GAs are predominantly amine-, glycol-, alcohol-, or carboxylic acid-based compounds (Mishra et al., 2017; Yang et al., 2019). However, their dosage critically affects not only grinding performance but also setting behavior, rheology, and long-term properties of cementitious systems (Assaad & Issa, 2014; Kobya et al., 2022; Kaya et al., 2024a, 2024b). In particular, amine-based additives such as triethanolamine (TEA) and triisopropanolamine (TIPA) have been reported to alter rheological characteristics and setting time in a dosage-dependent manner and may cause incompatibility with other admixtures (Assaad & Issa, 2015; Kobya et al., 2022; Kaya et al., 2024a, 2024b). These limitations, along with growing sustainability concerns and the need to improve energy efficiency in cement production, have prompted the exploration of polymer-based alternatives (Ma et al., 2015; Kobya et al., 2026).

Given their dual electrostatic–steric dispersion mechanism, PCEs have emerged as promising next-generation GAs (Dressel & Stark, 2010; Zhang et al., 2015). Experimental studies indicate that at approximately 0.1% by weight in the feed, PCEs can provide grinding performance comparable to that of conventional additives while simultaneously enhancing paste dispersion (Yang et al., 2019; He et al., 2021; Kaya et al., 2025).

In this context, the present study investigates two synthesized PCE-type grinding aids possessing identical main-chain length, side-chain length, side-chain density, and pH, but differing in side-chain-to-main-chain ratios (14 and 27) and molecular weight. Portland cements were produced by intergrinding clinker with the synthesized PCE-type GAs at dosages of 0.025%, 0.05%, and 0.1% by feed weight, alongside a reference cement without GA. The resulting mortars were evaluated for consistency retention at a constant dosage of water-reducing admixture.

2. MATERIALS & METHODS

Portland cements conforming to TS EN 197-1 were manufactured by intergrinding 96 wt.% clinker and 4 wt.% gypsum in a laboratory-scale ball mill to a target specific surface area of 4000 ± 100 cm²/g. The cement produced without any grinding aid (GA) was designated as the reference sample (R). Cements incorporating GAs were coded according to PCE type and dosage. The PCE-type GAs were further identified according to their side-chain-to-main-chain ratios (14 and 27). The main characteristics of the PCE-type GAs employed in this study are summarized in Table 1.

Table 1. Key properties of the synthesized PCE-based grinding aids

Properties	**PCE-14**	**PCE-27**
Solid content (%)	30.12	30.19
pH	3.54	2.94
Density (g/cm^3)	1.078	1.082
Mw* (g/mol)	37k	69k
Main chain length (g/mol)	4k	4k
Side-chain length (g/mol)	2.4k	2.4k
Side chain/main chain ratio	14	27

** Weight average molecular weight*

Mortar specimens were prepared in accordance with ASTM C109. The flow of fresh mortars was determined following ASTM C1437. For consistency retention assessment, a constant dosage of 0.20% water-reducing admixture by mass of cement was incorporated into all mixtures. Flow measurements were conducted immediately after mixing and subsequently at 20-minute intervals up to 60 minutes.

3. RESULTS & DISCUSSIONS

The time-dependent flow values of all mixtures are presented in Table 2. Figure 1 further illustrates the relationship between the initial flow and the corresponding relative flow measured after 60 minutes.

Table 2. The time-dependent flow values of all mixtures

	Time-dependent dispersion of mixtures containing fixed water-reducing admixtures (min)			
	0	**20**	**40**	**60**
R	24	20	19.5	15.8
PCE14-0.025	25.5	21.3	19.2	17.6
PCE14-0.05	24.8	21.1	18.8	16.5
PCE17-0.1	24.8	21	19.3	17
PCE27-0.025	22.8	19	17.8	15.3
PCE27-0.05	23.8	20.2	18.6	17.2
PCE27-0.1	24.3	21.5	20	17.5

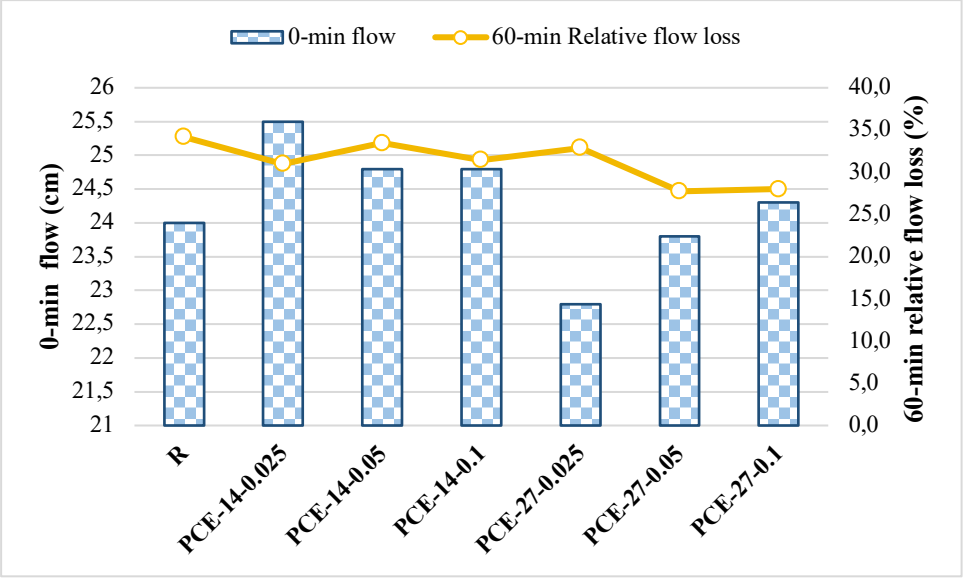


Figure 1. 0-min flow and consistency retention at 60 min (relative to 0-min)

As presented in Table 2 and Figure 1, no substantial change in the initial (0 min) flow values of the GA-containing mixtures was observed compared to the control, except the PCE-14-0.025 mixture, in which a PCE-type GA with a side chain-to-main chain ratio of 14 was incorporated at a dosage of 0.025%. The initial flow behavior appears to be governed by competing mechanisms. On the one hand, incorporating PCE-based GA enhances powder flowability, and its dispersing action in the mixture improves flow performance. On the other hand, the refinement and narrowing of the particle size

distribution induced by GA use tend to reduce flow values (Kobya et al., 2026). The distinctive behavior observed for the PCE-14 mixture at a low dosage (0.025%) is likely due to the dominance of its dispersion effects over the influence of particle size distribution refinement.

As illustrated in Figure 1, the relative consistency loss at 60 minutes was similar across all mixtures compared with their respective initial (0-min) flow values. Nevertheless, mixtures incorporating PCE-type GAs generally exhibited higher final flow values at 60 minutes than the reference. This behavior can be attributed to the reduced adsorption of the water-reducing admixture in cements produced with PCE-based GAs, leading to a greater fraction of non-adsorbed admixture remaining available in the pore solution (Kaya et al., 2024a, 2024b; Kobya et al., 2026). Previous studies have demonstrated that increased amounts of non-adsorbed superplasticizer enhance consistency retention (Karakuzu et al., 2021; Sha et al., 2020; Ma et al., 2022). Accordingly, the improved 60-minute flow values of PCE-based GA mixtures—particularly those containing PCE-14—are likely associated with the higher availability of non-adsorbed water-reducing admixture compared to the control.

4. CONCLUSIONS

This study evaluated the influence of the side-chain-to-main-chain ratio of PCE-based GAs on the consistency retention behavior of cementitious systems. The main findings can be summarized as follows:

- PCE-14, characterized by a lower side chain-to-main chain ratio, enhanced the initial flow performance when used at a low dosage (0.025%).
- The relative flow loss at 60 minutes remained comparable to the corresponding initial flow for all mixtures.
- Mixtures incorporating PCE-based GAs exhibited higher 60-minute flow values than the control mixture.
- Considering both initial flow and consistency retention, PCE-14 at low dosage and lower side chain/main chain ratio demonstrated the most favorable overall performance.

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EVALUATION OF INTEGRATED PEST MANAGEMENT STRATEGIES AGAINST TWO-SPOTTED SPIDER MITE (*Tetranychus urticae*)

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ABSTRACT

The two-spotted spider mite, ***Tetranychus urticae***, is one of the most destructive agricultural pests due to its wide host range, high reproductive capacity, and short generation time, causing significant economic losses in crop production. Under favorable environmental conditions, its population can increase rapidly, making control strategies more difficult and necessitating the development of sustainable management approaches. This situation is particularly critical in intensive production systems, where pest populations can quickly exceed economic threshold levels and pose serious risks to producers. Although chemical control has been widely used for many years, repeated applications of pesticides with similar modes of action have led to resistance development, suppression of natural enemies, and environmental concerns. In addition, increasing application frequency and costs limit the sustainability of chemical-based control strategies. These challenges highlight the inadequacy of single-control approaches and emphasize the need for integrating alternative methods. In this context, integrated pest management (IPM) has emerged as a key strategy for sustainable agricultural production. Chemical, biological, and cultural control methods used against the two-spotted spider mite were analyzed from a comparative and critical perspective; their effectiveness, cost, environmental impacts, and roles in resistance development were comprehensively evaluated. Furthermore, the contributions of integrating different control strategies to sustainable agricultural systems were addressed through a holistic approach.

In light of these evaluations, it is concluded that single control methods are insufficient for long-term management, whereas integrated and multi-faceted approaches provide more sustainable and effective solutions both environmentally and economically.

Keywords: *Tetranychus urticae*, integrated pest management, biological control, sustainable agriculture

1. Introduction

Tetranychus urticae Koch (Acari: Tetranychidae) is recognized as one of the most widespread and economically significant phytophagous mite species in agricultural production worldwide. Its broad host range, high reproductive capacity, short generation time, and ability to adapt rapidly to environmental changes contribute to this species causing persistent damage in numerous crop plants. It is reported that the pest feeds on more than 1,100 plant species, including vegetables, fruits, ornamental plants, field crops, and medicinal and aromatic plants (Van Leeuwen et al., 2013; Migeon & Dorkeld, 2025).

Tetranychus urticae feeds by forming colonies, particularly on the undersides of leaves, and sucking the contents of plant cells. This damage results in chlorotic spots on leaves, bronze discoloration, reduced photosynthetic activity, premature leaf drop, stunted growth, and a decline in product quality. In cases of high population density, plant physiology is severely disrupted, and yield losses can reach economically significant levels. It has been reported that the pest multiplies more rapidly in protected cultivation systems due to suitable temperatures and low humidity conditions (Grbić et al., 2011; Jakubowska et al., 2022).

In recent years, numerous studies have indicated that climate change, rising temperatures, and drought stress promote the population growth of *T. urticae.* It has been reported that under high-temperature conditions, the development period shortens, egg production per female increases, and the annual generation number rises. Consequently, it is predicted that red spider mite pressure will increase further in the future, particularly in the Mediterranean climate zone and in greenhouse cultivation (Gotoh et al., 2014; Assouguem et al., 2022).

For many years, the primary approach to controlling this pest has relied on the application of chemical acaricides. Numerous active ingredients, such as abamectin, bifenazate, spiromesifen, hexythiazox, and etoxazole, have been widely used at various times. However, it is known that *T. urticae* has developed resistance to many acaricides as a result of intensive and repeated applications. The species' high adaptive capacity, short generation time, and high genetic variation are cited as the primary factors accelerating the development of resistance (Van Leeuwen et al., 2010; Dermauw et al., 2013).

Overreliance on chemical control not only leads to resistance issues but also brings with it various risks related to the suppression of natural enemy populations, residue problems, environmental pollution, and human health. In particular, the negative impact of intensive pesticide applications on predatory mites can disrupt the biological balance and encourage outbreaks of secondary pests. For this reason, it is now more widely accepted that one-sided chemical control strategies are unsustainable (Barzman et al., 2015; Stenberg, 2017; Knapp et al., 2018).

In this context, Integrated Pest Management (IPM) stands out as one of the most environmentally and economically rational approaches to controlling *T. urticae.* IPM systems are based on the coordinated planning of regular population monitoring, decision-making based on economic damage thresholds, the use of biological control agents, cultural practices, the selection of resistant varieties, and selective pesticide applications. In recent years, successful results have been reported with the use of predatory mites such as Phytoseiulus persimilis, Neoseiulus californicus, and Amblyseius swirskii, and it has been noted that digital imaging and precision agriculture applications support IPM programs (Calvo et al., 2015; Zhao et al., 2023; Zhou et al., 2023).

Plant-based products, essential oils, biopesticides, and behavioral modulators are also gaining increasing importance as alternative tools in the control of *T. urticae.* In particular, global trends toward reducing the use of synthetic pesticides have increased interest in sustainable and environmentally friendly control strategies. In light of these developments, it has become essential to evaluate both traditional and innovative methods together (Isman, 2020; Pavela et al., 2016; Thomidis et al., 2024).

In this review, chemical, biological, cultural, and alternative methods used in the control of T. urticae are evaluated in light of current literature; the effectiveness, limitations, and importance of these strategies for sustainable agricultural production are comprehensively addressed from an integrated pest management perspective.

2. Biology, Distribution, and Economic Importance of *Tetranychus urticae*

Tetranychus urticae Koch (Acari: Tetranychidae) is a phytophagous mite species belonging to the order Prostigmata. It is widely distributed worldwide and causes significant economic losses in agricultural production. Thanks to its high ecological adaptability, the species can thrive in tropical, subtropical, and temperate climate zones and establish populations in open fields, greenhouses, and controlled production systems. Its wide geographic distribution and ability to feed on a wide variety of host plants have contributed to its global significance (Grbić et al., 2011; Migeon & Dorkeld, 2025;).

Morphologically, adult females typically have an oval body shape and may be yellowish-green, light brown, or reddish in color. The two dark dorsal spots on the body are the defining characteristic that identifies the species as the "two-spotted red spider." Male individuals are smaller than females and have a narrowed posterior section. Color variations may vary depending on the host plant, environmental conditions, and diapause status (Bolland et al., 2023).

The species' life cycle consists of the egg, larva, protonymph, deutonymph, and adult stages. Under suitable temperature conditions, the development period is quite short, and population growth occurs rapidly. In particular, it has been reported that within the 25–30 °C temperature range, the development time from egg to adult is significantly shortened and egg production per female increases. This situation causes the pest to form dense populations in a short time during warm periods (Gotoh et al., 2014; Riahi et al., 2018).

T. urticae has an arrhenotokous reproductive system, with males developing from unfertilized eggs and females from fertilized eggs. This biological characteristic facilitates the rapid reestablishment of populations and contributes to the rapid spread of resistance genes within the population. Additionally, its high reproductive capacity helps the pest survive even under pesticide pressure (Van Leeuwen et al., 2010).

The species is highly polyphagous and can feed on more than 1,100 plant species, including vegetables, fruit crops, ornamental plants, industrial crops, field crops, and medicinal and aromatic plants. High-value crops such as tomatoes, eggplants, peppers, cucumbers, beans, strawberries, cotton, apples, grapes, and roses are among its primary hosts. This broad host range allows it to sustain its life on different plants throughout the year and continuously find food sources in agricultural areas (Navajas, 1998; Migeon & Dorkeld, 2025).

The primary damage caused by the pest involves piercing leaf cells to suck out the cell sap. As a result of feeding, yellow-white spots appear on the leaf surface, and in later stages, bronzing, necrosis, and leaf drop are observed. The reduction in photosynthetic capacity inhibits plant growth, negatively affecting flowering and fruit set. Significant yield and quality losses have been reported, particularly in strawberry, bean, cotton, and vegetable production systems (Jakubowska et al., 2022; Attia et al., 2013).

The economic significance of *T. urticae* is not limited to direct damage alone. Intensive pesticide applications carried out to control the pest increase production costs, raise the risk of pesticide residues, and negatively impact natural enemy populations. Furthermore, the development of resistance to various acaricide groups in many countries further increases control costs. For this reason, the species is considered one of the pests of strategic importance—both biologically and economically—in modern agricultural production systems (Van Leeuwen et al., 2013; Dermauw et al., 2013).

In recent years, climate change, drought stress, and intensive production models have contributed to the earlier emergence of *T. urticae* populations and their reaching higher densities. It is predicted that the pest may pose a more serious threat in the future, particularly in hot and dry regions. Therefore, a thorough understanding of the species' biology and ecological requirements is of fundamental importance 1195ort he development of effective integrated pest management programs (Assouguem et al., 2022).

3. Chemical Control and Acaricide Resistance

Chemical acaricides have long been among the fastest and most effective control methods for Tetranychus urticae. The pest's ability to reach high population levels in a short time has led growers, particularly those cultivating high-value crops, to turn to chemical treatments that provide rapid results. The use of acaricides has been adopted as the primary control method in vegetable, fruit, strawberry, ornamental plant, and greenhouse production systems in many regions (Van Leeuwen et al., 2010; Jakubowska et al., 2022).

The acaricides used against this pest have different modes of action and demonstrate varying levels of success depending on the target life stage. Commonly used active ingredients in practice include abamectin, bifenazate, spiromesifen, spirodiclofen, hexythiazox, etoxazole, cyflumetofen, and new-generation compounds similar to cyflumetofen. While some products are more effective against eggs and early life stages, others achieve higher success rates during active stages. Therefore, application timing, dose, and the developmental stage of the population play a decisive role in control success (IRAC, 2024; Van Leeuwen et al., 2013).

As a result of the intensive and repeated application of chemical control, *T. urticae* has become one of the pests with the highest capacity to develop pesticide resistance. Today, resistance to numerous active ingredients has been reported worldwide, and in some populations, multiple resistance to more than one acaricide has been identified simultaneously. In particular, year-round pesticide pressure under greenhouse conditions is one of the key factors accelerating resistance development (Van Leeuwen et al., 2010; Assouguem et al., 2022).

The primary mechanisms involved in resistance development include target site mutations, the enhancement of metabolic detoxification systems, and physiological adaptations. While target site

mutations reduce binding at the pesticide's site of action, enzyme systems such as cytochrome P450 monooxygenases, esterases, and glutathione-S-transferases accelerate the breakdown of pesticides, thereby reducing toxicity. Genomic studies have shown that *T. urticae* possesses extensive detoxification gene families and that this trait facilitates the development of resistance (Dermauw et al., 2013; Van Leeuwen et al., 2013).

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Field studies conducted in recent years have revealed that resistance levels to certain active ingredients—particularly cyflumetofen, abamectin, and spiromesifen—have increased in some regions. Long-term monitoring programs indicate that resistance development can vary from region to region and is significantly influenced by local pesticide usage patterns. Therefore, resistance management programs must be planned based on regional data (İnak et al., 2022; Han et al., 2024).

The resistance issue not only reduces control efficacy but also leads to increased application frequency, higher dose usage, and rising production costs. Additionally, intensive pesticide use suppresses natural enemy populations, thereby reducing the effectiveness of biological control agents and limiting the success of IPM programs. In particular, the adverse effects of non-selective pesticides on predatory mites can pave the way for the resurgence of pest populations (Knapp et al., 2018; Jakubowska et al., 2022).

Cross-resistance is another significant problem in the management of *T. urticae.* The sequential use of active ingredients with the same mode of action or pesticides detoxified via similar metabolic pathways can cause resistance developed in one product to transfer to others. This situation narrows the range of available chemical options and shortens the lifespan of new active ingredients (Van Leeuwen et al., 2010).

For this reason, the modern approach to chemical pest control has shifted away from the heavy use of pesticides alone toward a more rational framework based on resistance management principles. Key strategies include rotating products with different modes of action, adhering to recommended doses, avoiding unnecessary applications, implementing population monitoring programs, and selecting products compatible with biological control agents. Mode-of-action classifications developed by IRAC provide important guidance to practitioners in this regard (IRAC, 2024).

In conclusion, while chemical acaricides remain effective tools for controlling *T. urticae* in the short term, they are not considered a sustainable solution on their own due to the development of resistance and environmental risks. Therefore, chemical control applications should be carefully planned within integrated pest management programs and used in a manner consistent with other control methods.

4. Biological Control

Biological control is recognized as one of the key components of sustainable agricultural systems in the management of *Tetranychus urticae*. Adverse effects associated with chemical control—such as the development of resistance, residue issues, environmental risks, and the suppression of natural enemy populations—have increased interest in biological control agents. In particular, the ability to maintain controlled environmental conditions in protected cultivation systems enables the successful use of predatory mites (Knapp et al., 2018; Jakubowska et al., 2022).

The most commonly used biological control agents against *T. urticae* are predatory mites belonging to the Phytoseiidae family. Species within this family, such as *Phytoseiulus persimilis*, *Neoseiulus californicus*, *Amblyseius swirskii*, and *Galendromus occidentalis*, play a significant role in commercial biological control programs because they are effective against different life stages of the pest. These predators can suppress population density by feeding on eggs, larvae, nymphs, and adult individuals (McMurtry et al., 2013; Knapp et al., 2018).

Phytoseiulus persimilis is known as one of the most effective specialized predators against *T. urticae.* Thanks to its high prey consumption capacity, short development time, and active foraging behavior, it yields particularly successful results under greenhouse conditions. However, this species' high dependence on prey and limited ability to utilize alternative food sources can make population sustainability difficult at low pest densities (McMurtry et al., 2013).

Neoseiulus californicus, on the other hand, has a more generalist feeding habit and can also feed on pollen and other small arthropods. This characteristic contributes to the maintenance of the predator population during periods of low pest density. Additionally, its greater tolerance to fluctuations in temperature and relative humidity has facilitated its widespread use in various production systems. Successful application examples have been reported in recent years in strawberries, vegetables, and ornamental plants (Knapp et al., 2018; Calvo et al., 2015).

Although *Amblyseius swirskii* is primarily used against pests such as whiteflies and thrips, it also has the potential to suppress low-density mite populations. Its ability to feed on pollen and survive on plants for extended periods allows it to be used as a supplementary predator in integrated pest management programs. This characteristic, which offers advantages in multi-pest production systems, is significant in IPM programs (Calvo et al., 2015).

Galendromus occidentalis is one of the important predator species used particularly in orchards and open-field systems. Its tolerance to hot and dry conditions ensures successful outcomes in some field and garden systems. Additionally, its relative tolerance to certain pesticides enhances its potential for use in conjunction with selective chemical applications (McMurtry et al., 2013).

Success in biological control applications depends not only on the selection of predator species but also on factors such as release timing, release dose, environmental conditions, pesticide use, and pest density. It has been reported that preventive releases conducted early in the season are more successful than corrective releases made later in the season against high pest populations. Furthermore, the use of selective products is of great importance to ensure that predators are not adversely affected by pesticide residues (Knapp et al., 2018; Zhao et al., 2023).

In recent years, approaches such as banker plant systems, pollen supplementation, habitat management, and supplementary food sources have also been used to enhance the sustainability of predatory mite populations. These methods contribute to the conservation of natural enemies, particularly during periods of low pest density, and enhance the success of IPM programs (Stenberg, 2017).

However, biological control also has certain limitations. High initial costs, sensitivity to suitable environmental conditions, delayed effects in rapidly rising pest populations, and predator losses due to unintentional pesticide use are among the significant challenges. Nevertheless, because it reduces pesticide use in the long term, contributes to resistance management, and supports environmental sustainability, biological control is considered one of the indispensable strategies for managing *T. urticae.*

In conclusion, predatory mites are among the most effective biological tools for controlling *T. urticae* and can achieve high success rates when used in conjunction with proper planning and other IPM components. Therefore, biological control practices should be further expanded in modern control programs.

5. Cultural Control and Cultivation Practices

Cultural control measures play a significant role in suppressing *Tetranychus u*rticae populations and reducing the need for chemical control. Cultural control practices aim to make the pest's habitat less suitable, enhance plant resilience, and limit population growth rates. They are considered a key component supporting biological and chemical methods, particularly within integrated pest management programs (Stenberg, 2017; Jakubowska et al., 2022).

Maintaining plant health and ensuring balanced growing conditions are fundamental elements in reducing red spider mite pressure. It has been reported that soft and watery plant tissues resulting from excessive nitrogen fertilization can promote the development of *T. urticae.* In contrast, balanced fertilization programs can limit pest development by enhancing the plant's physiological resilience. Similarly, it has been noted that plants under water stress are more susceptible to mite damage, whereas plants receiving regular irrigation exhibit higher tolerance (Wermelinger et al., 1985; Assouguem et al., 2022).

Temperature and relative humidity management are of particular importance in greenhouse cultivation. While high temperatures and low relative humidity accelerate the development of *T. urticae* populations, increasing relative humidity and preventing excessive temperatures can slow down pest development. For this reason, ventilation systems, shading practices, and proper irrigation management are key components of cultural control in greenhouse conditions (Zhang, 2003; Jakubowska et al., 2022).

Field and garden hygiene is another important component of cultural control. Removing post-harvest plant residues, controlling weeds, and clearing volunteer host plants reduce the pest's alternative habitats. Many weed species serve as intermediate hosts for *T. urticae* and can act as a source of population establishment for the new season. Therefore, managing the vegetation around the production area is of great importance (Migeon & Dorkeld, 2025).

Crop rotation and crop rotation practices can also yield beneficial results in some production systems. In particular, pest populations tend to become more established in areas where the same host plant is grown continuously. Rotation practices involving plants with different host characteristics can help reduce population density. However, due to their high polyphagy, crop rotation alone is often insufficient and must be combined with other methods (Navajas, 1998; Stenberg, 2017).

The use of resistant or tolerant varieties is one of the strategies gaining increasing importance in cultural control. Traits such as plant surface trichomes, leaf stiffness, secondary metabolite profile, and leaf anatomy can influence the pest's feeding and reproductive success. Differences in susceptibility levels observed among varieties have been reported, particularly in strawberries, beans, cotton, and vegetable crops. Therefore, variety selection is a critical factor that must be considered in the initial stages of control programs (Grbić et al., 2011; Jakubowska et al., 2022).

Ensuring that propagation material is clean is also critical for preventing the spread of the pest. Infected individuals transported via seedlings, saplings, and ornamental plant material can establish populations in new areas within a short period of time. Therefore, the use of certified propagation material, quarantine measures, and inspection of new plants before they are introduced into the production area are recommended (Migeon & Dorkeld, 2025).

In recent years, mulch, reflective plastic covers, and physical barrier systems have also been evaluated as part of cultural control measures. It has been reported that some of these practices limit the pest's movement onto plants, slow population growth by altering the microclimate, and support the activity of natural enemies. In particular, such practices can be integrated into IPM programs in intensive vegetable and strawberry cultivation (Stenberg, 2017).

The most significant advantage of cultural control methods is that they are environmentally friendly, do not create residue problems, and do not exert pressure for resistance development. However, their effects generally emerge slowly and may not be sufficient on their own. Therefore, cultural measures should be evaluated in conjunction with biological control, monitoring programs, and selective chemical applications when necessary.

In conclusion, cultural control practices serve as both fundamental and complementary tools for keeping *T. urticae* populations under control and are considered an indispensable component of sustainable production systems.

6. Plant-Based Products, Biopesticides, and Alternative Control Approaches

The resistance problem arising from the intensive use of synthetic acaricides in the control of *Tetranychus urticae*, along with residue risks and environmental concerns, has significantly increased interest in plant-based products and biopesticides in recent years. The use of alternative control tools is becoming increasingly widespread, particularly in organic farming systems, good agricultural practices, and production models aimed at low residue levels. Plant extracts, essential oils, microbial products, and naturally derived behavior modulators are among the notable options for *T. urticae* management (Isman, 2020; Jakubowska et al., 2022).

Plant-based products generally exert their effects on pests through various mechanisms, such as contact action, fumigant action, repellent action, feeding inhibition, and reduced oviposition. Additionally, it has been reported that certain plant compounds can exhibit growth-regulating effects and suppress egg hatching. This multifaceted mode of action suggests that the risk of resistance development may be lower compared to synthetic pesticides (Pavela et al., 2016).

Essential oils are one of the most extensively studied groups of natural products against *T. urticae.* In particular, oils derived from plants belonging to the Lamiaceae, Asteraceae, Rutaceae, Myrtaceae, and Apiaceae families have been reported to possess significant acaricidal potential. It has been reported that essential oils derived from thyme (*Thymus vulgaris),* rosemary (*Rosmarinus officinalis),* peppermint (*Mentha piperita),* lavender (*Lavandula angustifolia)*, eucalyptus (*Eucalyptus globulus*), and various *Artemisia* species are effective during different biological stages. The efficacy of these products varies depending on the components they contain, such as thymol, carvacrol, 1,8-cineole, menthol, linalool, and camphor (Pavela et al., 2016; Isman, 2020).

Products derived from neem (*Azadirachta indica)* have also been extensively studied for mite control. It has been reported that preparations containing azadirachtin suppress oviposition behavior, slow development, and cause mortality during the nymphal stages. Due to their low mammalian toxicity and environmental compatibility, neem-based products are considered important alternatives in IPM programs (Mordue & Nisbet, 2000; Jakubowska et al., 2022).

In addition to plant extracts, microbial biopesticides are also gaining attention. It has been reported that entomopathogenic fungi such as Beauveria bassiana, Metarhizium anisopliae, and Isaria fumosorosea can exert suppressive effects on *T. urticae* populations. The effectiveness of these organisms increases, particularly under high relative humidity conditions, and they can be used as a supportive component in biological control programs (Afifi, 2004; Jakubowska et al., 2022).

In recent years, surface-active biological compounds, plant-derived soaps, and rhamnolipid-based products have also emerged as prominent alternative control tools. It has been reported that these products disrupt cuticle integrity in pest individuals, reduce their mobility, and lower egg viability. They hold particular potential for use in programs targeting low residue levels, especially in greenhouse production systems (Thomidis et al., 2024).

The most significant advantages of plant- and biologically derived products include their environmental friendliness, short pre-harvest waiting periods, compatibility with natural enemies, and their ability to reduce resistance pressure. However, the efficacy of these products is significantly influenced by factors such as temperature, light, formulation structure, application rate, and target population density. Additionally, some products may require repeated applications due to their short residual life (Pavela et al., 2016; Isman, 2020).

Therefore, it is incorrect to view alternative products as a miracle solution on their own. The highest success is achieved in integrated pest management (IPM) systems where these products are planned in conjunction with predatory mites, cultural practices, and selective chemical applications. Particularly in areas with resistant populations, alternative products can enhance the effectiveness of IPM programs by contributing to the reduction of chemical pressure (Jakubowska et al., 2022).

In conclusion, plant-based products, biopesticides, and other natural formulations represent promising alternative tools in the control of *T. urticae.* However, standardization of these products, validation of their efficacy under field conditions, and the development of their economic feasibility are essential prerequisites for widespread adoption.

7. Integrated Pest Management (IPM) Strategies and Implementation Models

It has become clear today that approaches relying on a single method are insufficient in the long term for controlling *Tetranychus urticae.* The development of resistance in chemical control, environmental limitations in biological control, and the inadequacy of cultural measures alone have made it necessary to use different methods together in a planned manner. For this reason, Integrated Pest Management (IPM) is recognized as the most rational and sustainable approach to red spider mite management (Barzman et al., 2015; Stenberg, 2017).

The primary goal of IPM is not to completely eradicate the pest, but to maintain it at population levels that do not cause economic damage. In this approach, the decision-making process is based on criteria such as regular population monitoring, sampling results, the economic damage threshold, environmental conditions, and the presence of natural enemies. This prevents unnecessary pesticide applications, reduces costs, and minimizes environmental risks (Pedigo & Rice, 2014).

The first step in an effective IPM program for *T. urticae* is regular monitoring. Leaf sampling, counting individuals per plant, observing damage symptoms, and tracking natural enemy populations are crucial for determining the optimal timing of intervention. Low-density populations detected early can be more easily controlled using biological or cultural methods. In contrast, controlling high-density populations detected late becomes more difficult and costly (Jakubowska et al., 2022).

The integration of biological control agents into IPM programs is a fundamental component of modern pest management systems. In particular, the early release of predatory mites such as *Phytoseiulus persimilis*, *Neoseiulus californicus,* and *Amblyseius swirskii* yields effective results in keeping pest populations under control. When chemical applications are necessary, the use of selective products compatible with predatory mites is of critical importance for maintaining biological balance (Knapp et al., 2018; Zhao et al., 2023).

Cultural practices are also an integral part of IPM programs. Balanced fertilization, regular irrigation, greenhouse climate management, weed control, removal of infested plant material, and the use of resistant varieties help slow pest development and reduce the need for control measures. Microclimate management is particularly critical in greenhouse systems where hot and dry conditions promote pest development (Stenberg, 2017; Assouguem et al., 2022).

Chemical control is considered one of the last resort options in IPM programs. However, when intervention is necessary, selective, targeted, and timely applications provide significant benefits. Rotating the use of active ingredients with different modes of action, adhering to recommended doses, and avoiding unnecessary applications are essential for both resistance management and the protection of natural enemies (IRAC, 2024; Van Leeuwen et al., 2010).

In recent years, digital agriculture technologies and precision monitoring systems have opened new possibilities for IPM programs. Thanks to smartphone imaging systems, AI-supported diagnostic models, sensor-based climate monitoring, and early warning software, pest density can be determined more quickly, and intervention decisions can be made with greater accuracy. The potential for using these technologies is particularly high in high-value greenhouse and strawberry production systems (Zhou et al., 2023).

The success of IPM practices depends not only on technical methods but also on farmer training, advisory services, economic incentives, and local knowledge-sharing systems. It is critical for the sustainability of these programs that farmers use biological control agents correctly, understand pesticide rotation programs, and develop the habit of regular monitoring. For this reason, IPM is not merely a control method but also a knowledge-based management system (Barzman et al., 2015).

However, there are also some limitations to IPM implementation. Initial requirements for more information, monitoring costs, difficulties in obtaining biological agents, and expectations of quick results in the short term can limit implementation. However, when considering the long-term reduction in pesticide costs, the slowing of resistance development, environmental sustainability, and market advantages, it is evident that IPM programs also provide economic benefits (Stenberg, 2017).

In conclusion, the most successful approach to controlling *T. urticae* involves integrated systems where biological, cultural, chemical, and technological tools are planned to complement one another. Therefore, it is expected that IPM-based programs will become more widespread in the management of red spider mites in the future.

8. Future Outlook and Conclusion

Despite the progress made in recent years in controlling *Tetranychus urticae*, the pest's high adaptability, rapid reproductive capacity, and ability to develop tolerance to numerous control methods indicate that it will continue to pose a significant threat in the future. Climate change, the increase in global trade, the widespread adoption of intensive production systems, and pressure to use pesticides are among the primary factors that could increase the spread and economic significance of this pest. Therefore, future control programs must be more flexible, evidence-based, and multifaceted (Assouguem et al., 2022).

Advances in molecular biology and genomics are expected to make significant contributions to the management of *T. urticae* in the coming period. The early detection of resistance genes, the identification of genetic differences among populations, and the molecular-level monitoring of pesticide resistance will enable the development of more effective resistance management programs. Additionally, RNA interference (RNAi), gene silencing techniques, and target-specific biotechnological applications are considered among the innovative control tools of the future (Grbić et al., 2011; Van Leeuwen et al., 2013).

Digital agricultural technologies are also becoming increasingly important in red spider mite management. Thanks to AI-powered image processing systems, automated traps, sensor-based climate monitoring networks, and decision-support software, pest populations can be identified at an early stage, and intervention decisions can be made with greater precision. The economic feasibility of these technologies is particularly high in greenhouse and strawberry production systems where high-value crops are grown (Zhou et al., 2023).

In the field of biological control, the evaluation of new predatory mite species, improving the adaptation of existing commercial species to local conditions, and the development of supportive methods such as trap crop systems are anticipated. Additionally, the introduction of microbial biopesticides, plant-based products, and natural behavior modulators in more stable formulations will enhance the effectiveness of IPM programs (Knapp et al., 2018; Isman, 2020).

The widespread adoption of sustainable agricultural policies, increasing consumer sensitivity to pesticide residues, and demands for environmentally friendly production indicate that systems reducing chemical dependency in the future control of *T. urticae* will come to the forefront. In this context, integrated pest management is viewed not merely as a technical control approach but as a strategic

production model that addresses economic, environmental, and social sustainability collectively (Barzman et al., 2015; Stenberg, 2017).

However, in many regions, the widespread adoption of IPM practices requires farmer training, access to biological control agents, the establishment of regional monitoring networks, and the development of decision-support systems. Strengthening collaboration among universities, research institutions, the private sector, and farmers will play a critical role in translating innovative solutions into practical applications.

In conclusion, *Tetranychus urticae* remains one of the primary pests that will retain its significance in both current and future agricultural production systems. To successfully manage this pest, it is imperative to move away from traditional approaches reliant on chemical control and transition to integrated systems that combine biological, cultural, technological, and selective chemical methods. In the long term, sustainable, economical, and environmentally friendly control success will only be achievable through the widespread adoption of science-based IPM strategies.

9. General Conclusions and Recommendations for Implementation

Tetranychus urticae remains one of the primary pests threatening agricultural production worldwide due to its broad host range, short generation time, high reproductive potential, and ability to rapidly adapt to environmental conditions. In addition to the direct damage it causes to vegetables, fruits, ornamental plants, and industrial crops in both open-field and protected cultivation systems, its economic significance is quite high due to its role in increasing control costs and reducing product quality. It is expected that the pest will become an even more serious problem in production areas where hot and dry conditions are becoming more widespread (Assouguem et al., 2022).

Although chemical acaricides have been used as the primary control tool for many years, resistance has developed to many active ingredients as a result of intensive and repeated applications. This situation has not only reduced control efficacy but has also increased production costs by necessitating higher doses and more frequent applications. Additionally, residue issues, environmental risks, and the suppression of natural enemy populations have limited the sustainability of chemical control systems (Van Leeuwen et al., 2010; Jakubowska et al., 2022).

Biological control agents, particularly predatory mites, offer successful and environmentally friendly alternatives for managing *T. urticae.* Species such as *Phytoseiulus persimilis, Neoseiulus californicus*, and *Amblyseius swirskii* can effectively suppress pest populations under suitable conditions. However, the level of success depends on release timing, environmental conditions, pesticide use, and the effectiveness of monitoring programs (Knapp et al., 2018; Calvo et al., 2015).

Cultural practices and cultivation techniques are also key components of control programs. Balanced fertilization, regular irrigation, weed control, use of clean seedlings, greenhouse climate management, and selection of resistant varieties help slow the development of pest populations and enhance the success of other control methods. Plant-based products, essential oils, and biopesticides, meanwhile, emerge as important complementary tools, particularly in production systems aiming for low residue levels (Pavela et al., 2016; Isman, 2020).

The overall assessment of this review clearly demonstrates that strategies relying on a single method for controlling *T. urticae* are insufficient in the long term. The most successful results are achieved through integrated pest management systems that combine regular monitoring, decision-making based on economic damage thresholds, the conservation and use of biological control agents, cultural practices, alternative crops, and selective chemical applications when necessary (Barzman et al., 2015; Stenberg, 2017).

To develop more effective control programs in the future, it is necessary to prepare regional resistance maps, assess local predator species, expand the use of digital monitoring technologies, and strengthen producer education programs. Additionally, developing new prediction models that account for the effects of climate change on pest populations is crucial.

In conclusion, sustainable control of *Tetranychus urticae* is not possible through approaches reliant solely on pesticide use. IPM-based strategies that address environmental, economic, and biological factors together will continue to be the most effective and sustainable solution for red spider mite management in the future.

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Environmental Determinants of Population Dynamics of Two-Spotted Spider Mite (*Tetranychus urticae*)

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ABSTRACT

The two-spotted spider mite, ***Tetranychus urticae***, is one of the most destructive agricultural pests due to its wide host range, high reproductive capacity, and short generation time, causing significant economic losses in crop production. The population dynamics of this pest are highly sensitive to environmental factors, particularly temperature, humidity, and host plant characteristics, which play a critical role in its population development. This situation leads to rapid population growth and the quick exceedance of economic threshold levels, posing serious risks for agricultural production systems. Temperature directly affects developmental time, number of generations, and lifespan, with increasing temperatures accelerating development and enhancing population growth. In contrast, low humidity conditions may increase survival rates, thereby supporting higher population densities. In addition, host plant species, physiological condition, and nutritional quality significantly influence reproductive capacity and developmental performance. Furthermore, agricultural practices, cultivation techniques, and microclimatic conditions play a decisive role in population fluctuations. In particular, greenhouse production systems provide favorable environmental conditions that facilitate rapid increases in pest populations. Moreover, the interaction among environmental factors significantly influences the temporal and spatial distribution of pest populations. Environmental factors affecting the population dynamics of the two-spotted spider mite were comparatively examined, and their impacts on pest management were comprehensively evaluated. In light of these evaluations, considering environmental factors is essential for developing more effective, sustainable, and targeted pest management strategies.

Keywords: *Tetranychus urticae*, environmental factors, temperature, humidity, population dynamics

ÖZET

Kırmızı örümcek, *Tetranychus urticae*, geniş konukçu aralığı, yüksek üreme kapasitesi ve kısa generasyon süresi nedeniyle tarımsal üretimde önemli ekonomik kayıplara neden olan başlıca zararlılardan biridir. Zararlının populasyon dinamikleri çevresel faktörlere yüksek derecede duyarlılık

göstermekte olup, özellikle sıcaklık, nem ve konukçu bitki özellikleri populasyon gelişimi üzerinde belirleyici rol oynamaktadır. Bu durum, zararlı populasyonlarının kısa sürede artmasına ve ekonomik zarar eşiğinin hızla aşılmasına neden olmaktadır. Sıcaklık, gelişim süresi, döl sayısı ve yaşam süresi üzerinde doğrudan etkili olup, artan sıcaklık koşullarında zararlının gelişim süresi kısalmakta ve populasyon artışı hızlanmaktadır. Buna karşılık, düşük nem koşulları bireylerin hayatta kalma oranını artırarak populasyon yoğunluğunu destekleyebilmektedir. Ayrıca, konukçu bitki türü, bitkinin fizyolojik durumu ve besin içeriği, zararlının üreme kapasitesi ve gelişim performansı üzerinde önemli etkiler göstermektedir. Bununla birlikte, tarımsal uygulamalar, yetiştirme teknikleri ve mikroklimatik koşullar da populasyon dalgalanmalarında belirleyici olmakta; özellikle örtü altı üretim sistemlerinde oluşan uygun çevresel koşullar zararlı populasyonlarının hızlı artışına zemin hazırlamaktadır. Bunun yanı sıra, çevresel faktörlerin birbiriyle etkileşimi, zararlı populasyonlarının zamansal ve mekânsal dağılımını da önemli ölçüde etkilemektedir. Kırmızı örümcek populasyon dinamiklerini etkileyen çevresel faktörler karşılaştırmalı bir bakış açısıyla ele alınmış ve bu faktörlerin zararlı yönetimi üzerindeki etkileri kapsamlı şekilde değerlendirilmiştir. Bu değerlendirmeler ışığında, çevresel faktörlerin dikkate alınmasının, zararlı ile mücadelede daha etkili, sürdürülebilir ve hedefe yönelik yönetim stratejilerinin geliştirilmesine önemli katkılar sağladığı ortaya konmaktadır.

Anahtar Kelimeler: *Tetranychus urticae*, çevresel faktörler, sıcaklık, nem, populasyon dinamikleri

1. Introduction

Tetranychus urticae Koch (Acari: Tetranychidae), commonly known as the red spider mite, is one of the most significant phytophagous mite species causing economic losses in agricultural production worldwide. Due to its polyphagous feeding habits, the species can cause damage to over 1,100 plant species, including vegetables, fruits, field crops, ornamental plants, and industrial crops. A wide host range, short life cycle, high reproductive capacity, and the ability to adapt rapidly to environmental conditions enable this pest to establish persistent and destructive populations in various agroecosystems (Van Leeuwen et al., 2015; Migeon & Dorkeld).

The damage caused by *T. urticae* primarily involves piercing the epidermal cells of leaves with its style-like mouthparts to suck out the cellular contents. As a result of feeding, chlorotic spots, bronze discoloration, reduced photosynthetic capacity, premature leaf drop, and stunted plant growth in cases of severe infestation occur on the leaf surface. Especially at high population densities, the web structures formed on the plant surface not only contribute to the pest's protection but can also reduce the effectiveness of chemical control. Therefore, the economic impact of the pest is not limited to direct feeding damage alone but extends to broader dimensions, including quality losses and control costs (Attia et al., 2013).

In recent years, climate change, intensive production systems, the widespread adoption of protected cultivation, and the rise in pesticide resistance have further heightened the significance of *T. urticae*. In particular, rising temperatures and dry conditions accelerate the species' development rate, leading to increased reproduction; this, in turn, results in more frequent population outbreaks. Similarly, the favorable microclimatic conditions created in greenhouse environments and low natural enemy pressure can allow the pest to remain active throughout the year (McMurtry et al., 2013; Van Leeuwen et al., 2015;).

Effective management of a pest species depends on a detailed understanding of the factors determining its population dynamics. *T. urticae* population density is influenced by numerous environmental variables, including temperature, relative humidity, photoperiod, host plant species, plant nutritional status, presence of natural enemies, cultivation system, and agricultural practices. The individual or combined effects of these factors determine the temporal growth, seasonal fluctuations, and spatial distribution of populations.

In this study, the primary environmental factors influencing *T. urticae* population dynamics were evaluated in light of the current literature; the importance of these factors for pest management and sustainable control strategies was comprehensively addressed.

2. Agricultural Importance of *Tetranychus urticae*

Tetranychus urticae is one of the most common mite pests in open-field and greenhouse cultivation systems worldwide. It causes economic damage to numerous cultivated plants, primarily tomatoes, peppers, aubergines, beans, strawberries, apples, citrus fruits, cotton, and ornamental plants. It particularly reduces market value due to quality loss in vegetable and fruit production, leading to serious problems in export-oriented production.

One of the most important biological characteristics affecting the species' success is its short generation time. Under suitable temperature conditions, development from egg to adult can be completed in as little as a week, and females can lay numerous eggs throughout their lives. This causes

the population density to increase exponentially in a short time. Furthermore, due to its arrhenotokous reproductive system, male individuals can develop from unfertilised eggs, facilitating population re-establishment (Van Leeuwen et al., 2015).

Another significant problem is its capacity to develop high resistance to pesticides. *T. urticae* is considered one of the exemplary species that has developed resistance to numerous acaricide agents worldwide. Therefore, strategies based solely on chemical control are often insufficient, making integrated pest management approaches necessary (Dermauw et al., 2013).

2. Effect of Temperature on *Tetranychus urticae* Population Dynamics

Temperature is one of the most important abiotic factors determining the population development of Tetranychus urticae. Although the species can develop over a wide temperature range, development time, lifespan, egg yield, and population growth rate vary significantly depending on temperature. In general, an increase in temperature shortens development time and increases the number of generations up to a certain optimum point. Therefore, sudden population increases are observed more frequently in agricultural areas, especially during hot and dry periods (Carey & Bradley, 1982; Gotoh et al., 2014).

Laboratory studies have reported that *T. urticae* can actively develop within a temperature range of approximately 15–35°C, with its biological performance peaking, particularly between 25–30°C. At these temperatures, the development time from egg to adult is reduced, the number of eggs laid per female increases, and net reproductive capacity rises. Conversely, at lower temperatures, embryonic development slows, nymphal stages are prolonged, and the population growth rate declines (Sabelis, 1982; Gotoh et al., 2014).

Some studies indicate that females achieve their highest egg production around 30°C, but when the temperature exceeds the optimum, lifespan shortens and fertility decreases. Especially at temperatures above 35°C, although development may continue briefly, prolonged exposure can cause physiological stress, increased mortality, and population suppression. This demonstrates that the biological effect of temperature is not linear but depends on threshold values (Logan et al., 1976).

Under field conditions, the effect of temperature is often reflected in seasonal population fluctuations. Populations, which begin at low densities in spring, increase rapidly with rising temperatures in summer and reach their highest levels in most production areas during July–August. Population density then decreases as temperatures fall in autumn. Therefore, temperature data are used as an important indicator in early warning systems and for control timing (Carey & Bradley, 1982; Gotoh et al., 2014). It is considered that rising temperatures due to climate change may also have significant consequences for *T. urticae*. Longer and warmer vegetation periods may result in more offspring, expansion of the species' distribution area, and increased potential for economic damage. In addition, the weakening of plant defence mechanisms under heat stress can indirectly increase the pest's success rate (Van Leeuwen et al., 2015).

4. The Effect of Humidity on *Tetranychus urticae* Population Dynamics

Relative humidity is an important environmental factor affecting the development, lifespan, egg-laying success, motility, and dispersal capacity of *T. urticae* populations on plants. Although temperature is often considered the primary determinant, changes in humidity levels can significantly influence the population density of this pest, especially under microclimate conditions. Therefore,

relative humidity, together with temperature, should be considered when evaluating *T. urticae* population dynamics (Van Leeuwen et al., 2015; Attia et al., 2013).

In general, *T. urticae* is a species that develops more successfully in hot and relatively dry environmental conditions. Under low relative humidity, the mobility of individuals can increase, feeding activity on the leaf surface intensifies, and population growth can accelerate. Especially in the summer months, the combination of low humidity and high temperature can cause sudden population increases in open-field production systems. Physiological stress in plants during drought periods can also indirectly support pest development. Weakening of defence mechanisms and changes in nutrient balance in plants under water stress can create a more favourable feeding environment for *T. urticae* (Huberty & Denno, 2004; Ximénez-Embún et al., 2017).

High relative humidity levels, however, can limit population development under certain conditions. It has been reported that high humidity can suppress the viability of eggs and juvenile individuals, and that the humid environment created on the leaf surface can favour some natural enemies and pathogenic microorganisms. However, the effect of humidity should often be evaluated together with temperature. While moderate humidity can support development under suitable temperature conditions, the combination of high humidity and low temperature can reduce the growth rate (Attia et al., 2013; Van Leeuwen et al., 2015).

The effect of humidity in field and greenhouse conditions often appears through microclimatic differences. In densely planted areas, poorly ventilated greenhouses, and systems with intensive irrigation, the moisture level beneath the leaves increases, which can influence the distribution of pests on the plant. Especially in greenhouse production, the combined management of temperature and humidity plays an important role in keeping *T. urticae* populations under control. Ventilation, shading,

and irrigation strategies affect not only plant development but also pest control (McMurtry et al., 2013; Hoy, 2016).

In the context of climate change, longer drought periods are expected in many regions as temperatures rise. This may lead to more frequent combinations of low humidity and high temperatures, causing *T. urticae* population outbreaks to become more widespread in the future. Therefore, it is important to include the relative humidity parameter in climate-based risk models (Van Leeuwen et al., 2015).

In conclusion, relative humidity is an important environmental variable that should be considered alongside temperature in the population dynamics of *T. urticae*. Especially as the combination of low humidity and high temperature promotes population growth, humidity management should be considered a crucial component of integrated pest management strategies in greenhouse production systems and intensive agricultural areas.

5. The Effect of Host Plant on *Tetranychus urticae* Population Dynamics

The host plant species is one of the most important biotic factors determining *T. urticae* population density, development period, lifespan, egg yield, and damage level. As a polyphagous species, *T. urticae* can live on numerous cultivated and weed species; however, it does not exhibit the same biological success on every plant species. The pest's performance on different plants varies depending on the plant's morphological structure, nutrient content, leaf anatomy, and defence mechanisms (Kant et al., 2008; Migeon & Dorkeld, 2025).

Nutritional differences between plant species directly affect the reproductive capacity of red spider mites. It has been reported that in nitrogen-rich, soft-textured, and fast-growing plants, the number of eggs per female increases, the development period shortens, and the population growth rate rises. In contrast, in plants with fibrous leaf tissue, rich in phenolic compounds, or high in defence metabolites, development occurs more slowly, and the survival rate of individuals may decrease (Awmack & Leather, 2002; Agrawal, 2011).

Leaf surface characteristics are also important factors affecting the success of mites. Factors such as leaf hair density, waxy layer thickness, stomatal structure, and epidermal hardness can influence both mobility and feeding behaviour. Some studies have indicated that mite mobility can be limited on leaves with a dense hair structure, while in some cases, the hair structure can reduce the pressure from natural enemies, resulting in a favourable outcome for the pest (Sabelis, 1985).

The physiological age of the plant is also important for population dynamics. Due to the higher nutritional quality in young leaves, mite density is often higher in new shoots. In ageing leaves, while reduced defence capacity may sometimes facilitate feeding, the low nutritional quality can limit the reproduction rate. Therefore, the distribution of the pest on the plant often changes in parallel with the phenological stage of the plant (Kant et al., 2008).

Plant stress conditions also significantly affect the development of *T. urticae* populations. Physiological changes in the plant during drought, excessive fertilisation, or unbalanced irrigation can increase the amount of free amino acids and soluble sugars in leaf tissues, which may promote pest

development. Many studies have reported an increase in red spider mite density, particularly in areas with high nitrogen fertilisation (Huberty & Denno, 2004; Ximénez-Embún et al., 2017).

Weeds are also important as alternative hosts under field conditions. Populations that survive on weeds during periods when the crop is absent can return to the main crop and become a source of infestation when suitable conditions arise. Therefore, weed management is important not only for reducing competition but also for limiting intermediate hosts of red spider mites (Jeppson et al., 1975).

In conclusion, the host plant is one of the key biotic factors shaping the population dynamics of *T. urticae*. The use of resistant varieties, balanced fertilisation, reduction of plant stress, and control of alternative hosts should be considered among the effective cultural control measures in pest management.

6. The Effect of Agricultural Practices and Cultivation Systems on *Tetranychus urticae* Population Dynamics

*Tetranychus u*rticae population density is significantly influenced not only by climatic and plant factors, but also by agricultural practices and cultivation systems. Practices such as irrigation, fertilisation, pruning, plant density, weed management, pesticide use, and open field or greenhouse production directly or indirectly alter the pest's developmental environment. Therefore, the production technique is considered one of the fundamental elements in understanding population fluctuations (Van Leeuwen et al., 2015; Hoy, 2016).

Irrigation management has a significant impact on red spider mite populations, especially in arid regions. Plant water stress resulting from insufficient irrigation can cause nutritional changes in leaf tissues, promoting mite development. Conversely, regular and balanced irrigation can increase the physiological resilience of the plant and reduce pest pressure. However, dense vegetation and a humid microclimate resulting from excessive irrigation can lead to different outcomes in some production systems (Huberty & Denno, 2004).

Fertilisation practices are also important in population development. In particular, excessive nitrogen fertilisation can increase the reproductive capacity of *T. urticae* by increasing the formation of free amino acids and soft tissue in leaf tissues. Balanced feeding programmes, on the other hand, can increase plant resistance and limit pest success. Therefore, fertilisation programmes should be planned not only for yield but also for pest management (Awmack & Leather, 2002).

Plant density and pruning practices are other factors affecting the microclimate in the field or greenhouse. In densely planted areas, local population increases can occur due to reduced air circulation, the formation of suitable temperature conditions on the leaf surface, and the difficulty of control applications. Regular pruning and plant thinning both increase aeration and help remove infested leaves (Hoy, 2011; McMurtry et al., 2013).

Weed management is also important. Weeds along field edges and between rows serve as alternative hosts for T. urticae and can create a source of re-infestation at the beginning of the season. Failure to control weeds, especially in the post-harvest period, allows the pest to survive in the environment (Jeppson et al., 1975).

Pesticide use can have a twofold effect. Inappropriate or intensive insecticide use can suppress natural enemy populations, causing red spider mites to become secondary pests. In addition, repeated acaricide applications accelerate resistance development and reduce control success. Therefore, the use of selective preparations and rotation of the mode of action are of great importance (Dermauw et al., 2013; Van Leeuwen et al., 2015).

Greenhouse cultivation systems are among the most suitable habitats for *T. urticae*. In greenhouses, relatively constant temperatures throughout the year, low rainfall, limited natural enemy pressure, and dense plant populations allow populations to reach economically damaging levels in a short time. Therefore, regular monitoring, the use of biological control agents, and climate control are more critical in greenhouse production than in open fields (McMurtry et al., 2013).

In conclusion, agricultural practices and cultivation system choices are manageable factors that directly affect *T. urticae* population dynamics. Adopting appropriate cultural practices, balanced nutrition, water management, and integrated pest management principles are fundamental strategies for keeping the pest under control.

7. Interaction of Environmental Factors and Population Fluctuations

The population dynamics of *T. urticae* often exhibit a complex structure that cannot be explained by a single environmental factor. The interactions between temperature, relative humidity, host plant characteristics, cultivation system, presence of natural enemies, and agricultural practices determine the temporal and spatial variation of population density. Therefore, seasonal increases or sudden population

explosions of the pest usually occur when more than one factor becomes favorable simultaneously (Sabelis, 1982; Van Leeuwen et al., 2015).

The combined effect of temperature and humidity is one of the key combinations determining the rate of population increase. The simultaneous occurrence of high temperature and low humidity conditions creates an ideal growth environment for *T. urticae* in many production areas. Under these conditions, the development period is shortened, egg production increases, and the dispersal capacity of individuals is enhanced. Especially during the summer months, prolonged hot and dry weather conditions can lead to serious infestations in open-field production systems (Carey & Bradley, 1982).

The relationship between host plant quality and climatic factors is also important. Physiological changes occurring in leaf tissues in plants under drought stress, when combined with temperature, can further accelerate pest development. Similarly, leaf tissues softened as a result of excessive nitrogen fertilization support population growth under suitable temperature conditions. This shows that plant nutrition programs cannot be evaluated independently of environmental conditions (Huberty & Denno, 2004; Ximénez-Embún et al., 2017).

Natural enemy populations are also affected by environmental interactions. Predator mites and other biological control agents often show the highest performance in certain temperature and humidity ranges. However, in some cases, the environmental tolerance limits of the pest mite and natural enemies may differ. For example, while the *T. urticae* population increases rapidly under high temperature conditions, the inability of predator species to multiply at the same rate can disrupt the biological balance in favor of the pest (McMurtry et al., 2013).

The cultivation system also shapes the effect of environmental factors. While rainfall, wind, and daily temperature variations can limit populations in open field production, the pest becomes more advantageous in greenhouse conditions due to the more stable climate structure. Especially in poorly ventilated greenhouses, the increase in temperature and low natural enemy pressure can lead to the formation of dense populations in a short time (Hoy, 2011; McMurtry et al., 2013).

From a spatial distribution perspective, *T. urticae* populations are often not homogeneously distributed within the field. Sunny edge rows, water-stressed areas, poorly ventilated areas, or parts with high weed density can create local hotspots, leading to population clusters. Therefore, the heterogeneous structure within the field should be taken into account in control programs, and monitoring studies should not be carried out only from a single point (Jeppson et al., 1975).

In conclusion, *T. urticae* population fluctuations are shaped by the simultaneous influence of numerous environmental factors. Due to this complex structure, prediction models based on only a single variable are often insufficient; More effective management strategies require integrated and multivariate approaches.

8. Use of Environmental Factors in *Tetranychus urticae* Management

Achieving successful results in the control of *T. urticae* depends on the correct assessment of the pest's biology and the environmental factors affecting population growth. In traditional control programs, chemical applications are often resorted to after population density is observed; however, this approach can lead to increased economic losses and accelerate the development of resistance. In contrast, monitoring environmental indicators such as temperature, humidity, plant growth status, and

production system allows for the development of early warning and preventive control strategies (Dermauw et al., 2013; Van Leeuwen et al., 2015).

Temperature data is one of the most commonly used parameters in population prediction models. Since the development rate of the pest is directly dependent on temperature, generation periods can be predicted with degree-day models or temperature-based prediction systems, and periods when density increase is expected can be predicted in advance. Thus, monitoring frequency can be increased, the release of biological control agents can be planned for appropriate times, and chemical control can be applied only when necessary (Carey & Bradley, 1982).

Relative humidity and ventilation management are important tools, especially in greenhouse production systems. In greenhouses, appropriate climate control can prevent the occurrence of excessively hot and dry conditions, limiting the rapid reproduction of the pest. The effective use of ventilation windows, shading practices, and regular irrigation programs not only support plant development but can also create a microclimatic environment that suppresses mite density (McMurtry et al., 2013).

Host plant management is also an important component of environmentally based control strategies. The preference for resistant or tolerant varieties, the application of balanced fertilization programs, and the reduction of plant stress can limit the developmental success of *T. urticae*. In particular, avoiding excessive nitrogen fertilization and regular irrigation are among the cultural measures that reduce the population growth rate (Huberty & Denno, 2004; Awmack & Leather, 2002).

Environmental factors should also be considered in biological control programs. The effectiveness of natural enemies, primarily predatory mites, varies depending on temperature and humidity conditions. Therefore, the release of predator species such as Phytoseiulus persimilis and Neoseiulus californicus yields more successful results when environmental conditions are favorable. Furthermore, protecting

natural enemies through selective pesticide use is of great importance for long-term stability (McMurtry et al., 2013).

Chemical control should be considered the final step in integrated systems. When population density exceeds the economic damage threshold, it is recommended to use selective and licensed acaricides on a rotation basis. However, supporting application timing with environmental data is critical to reducing unnecessary spraying and slowing down resistance development (Dermauw et al., 2018; Van Leeuwen et al., 2015).

In conclusion, actively using environmental factors in pest management supports not only the suppression of *T. urticae* populations but also the achievement of economic, environmental, and sustainable production goals. Therefore, modern control programs should be based on a proactive management approach rather than direct intervention.

9. Conclusion and Recommendations

*Tetranychus u*rticae is one of the main mite pests threatening agricultural production worldwide due to its wide host range, short generation time, high reproductive capacity, and ability to develop resistance to pesticides. When the population dynamics of the species are examined, it is seen that density changes are not only due to biological characteristics but also to the combined effect of numerous environmental factors such as temperature, relative humidity, host plant structure, cultivation system, presence of natural enemies, and applied agricultural practices.

Temperature is one of the key factors directly affecting the development period and reproductive capacity of the pest. Especially in hot periods, the shortening of the generation time leads to the formation of high population densities in a short time. Low humidity conditions often support this process, leading to the pest becoming a more serious problem in arid and hot climates. Conversely, high humidity, rainfall, and unsuitable temperature values can suppress population development in some periods.

Host plant characteristics are also important elements determining population success. Plant species, leaf anatomy, nutrient content, and physiological condition directly affect the pest's developmental performance. Increased red spider mite infestation, particularly in plants experiencing water stress or excessive nitrogen fertilization, highlights the importance of cultural practices in pest control.

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SOCIAL INTEGRATION: A HUMANISTIC VISION BASED ON THE FRIDAY SERMONS OF MUHAMMAD AL-SADR

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ABSTRACT

This paper examines the concept of social integration as articulated in the forty-five Friday sermons delivered by Muhammad al-Sadr during (1997–1999 CE). Drawing on qualitative textual analysis of the sermon corpus, the study identifies a coherent and systematic humanistic vision of social integration that pervades al-Sadr's discourse, one grounded in Islamic theological principles yet addressing universal human concerns of belonging, solidarity, communal obligation, and civic participation. The paper argues that al-Sadr's Friday sermons constitute not merely a religious ritual, but a deliberate social engineering project aimed at rebuilding the fractured social fabric of Iraqi Shia society under conditions of authoritarian repression and enforced isolation. The study maps sixteen thematic categories of social integration discourse across the corpus, analyzes the rhetorical and argumentative mechanisms through which al-Sadr constructs his vision, and situates his model within contemporary sociological frameworks of social capital, community cohesion, and humanistic sociology. The findings demonstrate

that the Sadrist humanistic vision of social integration anticipates and parallels key insights of modern social theory while remaining rooted in distinctively Islamic ethical and theological foundations.

Key Words: Social Integration, Sadrist School, Muhammad al-Sadr, Friday Sermons, Islamic Humanism, Social Cohesion, Iraqi Society, Religious Discourse

INTRODUCTION

Background and Context: Social integration, the process through which individuals and groups are bound together into a functioning, mutually supportive community, has been a central concern of sociological inquiry since Émile Durkheim's foundational studies of solidarity and anomie in the late nineteenth century. In contemporary discourse, social integration encompasses the dimensions of social cohesion, civic participation, shared identity, mutual obligation, and the structures that sustain collective life against the centrifugal forces of individualism, inequality, and political disruption. In the Iraqi context of the late 1990s, the conditions for social integration were severely compromised. The Ba'athist regime's systematic dismantling of civil society, the devastation of two decades of war and economic sanctions, the forced marginalization of the Shia majority, and the deliberate atomization of community life had produced a social landscape of profound fragmentation, distrust, and despair. It was in this context that al-Sadr (1943–1999), founder of what is now known as the Sadrist School, launched his extraordinary program of public Friday sermons at the mosque of Kufa, beginning in 1997. To effectively navigate the complex intellectual genealogy of the Sadrist movement, this paper utilizes a conceptual mapping strategy. Visualizing the movement’s evolution from Muhammad al-Sadr’s late-1990s theology to the contemporary political reality of Sayyid Muqtada al-Sadr requires a multi-dimensional approach. The mind map presented in Figure 1 serves as an analytical anchor, illustrating the interconnectedness of theological premises and their subsequent political applications. At the core of this intellectual architecture lies Friday Sermon (45). The map identifies this text not as a historical relic, but as the generative source, or “conceptual DNA”, of the movement. Radiating from this center are the three foundational pillars of this research: “reform from the margins,” the “speaking seminary,” and a redefined “national belonging.” Each pillar branches outward to link the martyr’s initial discourse

with the movement's later operational shifts, such as public protest culture, social patronage, and cross-sectarian political narratives (Al-Sadr, 1999; Fajir & Bilal, 2022; Abbas & Taan, 2023).

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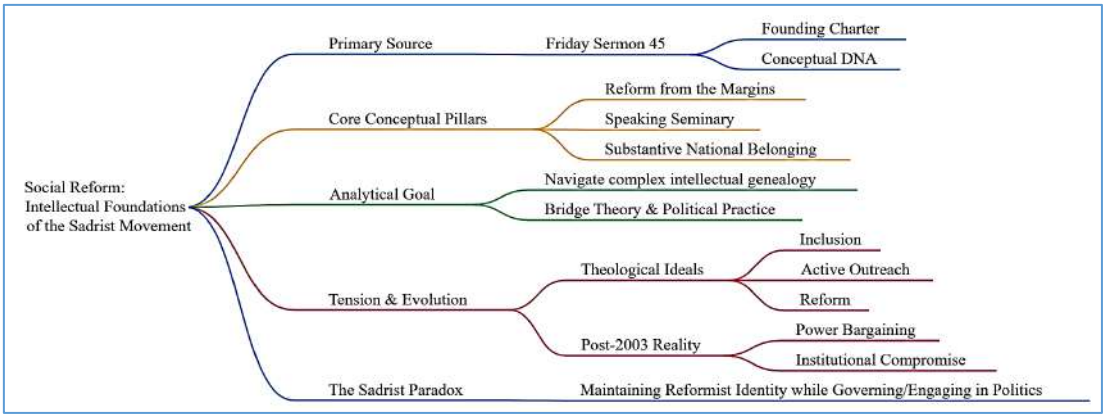


Fig. 1 The interconnectedness of theological premises and their subsequent political applications

Furthermore, the map highlights the distinct zone of friction between these theological ideals and the exigencies of Iraq's post-2003 political landscape. By situating the "speaking seminary" concept against the backdrop of state-building, the map underscores the central tension inherent in the movement's duality: functioning simultaneously as a protest-based reformist entity and a stakeholder in government power. Ultimately, this visual representation serves as a roadmap for the reader, ensuring that the theoretical abstractions discussed throughout this paper remain grounded in a clear structural narrative. It clarifies how a sermon delivered on the periphery of Iraqi society evolved into a governing philosophy. By providing this holistic view, the study invites the reader to trace not only the continuity of thought but also the inevitable metamorphosis that occurs when religious ideology is transcribed into the volatile language of democratic participation. The 45 Sermons as a Social Document: The corpus of forty-five Friday sermons under analysis in this paper is not simply a collection of religious addresses. It is, as this study demonstrates, a systematic and sustained intervention in the social life of a community in crisis. Al-Sadr used the sermon platform, the most accessible and widely attended public forum available in Iraqi Shia society, to articulate, model, and advocate for a comprehensive vision of social integration grounded in Islamic humanistic values. This vision is not presented in abstract theoretical terms. It is embedded in the texture of the sermons themselves: in the specific topics al-Sadr chose to

address, in the problems he identified, in the solutions he proposed, and, crucially, in the social dynamics he enacted through the very act of delivering the sermons to tens of thousands of congregants week after week (Al-Sadr, 2003; Issam, 2012; Abu al-Abra, 2016; Iman, Maliha & Wathiq, 2018; Abbas & Taan, 2023).

Research Objectives: (1) To identify and systematically map the themes of social integration present across the 45 sermon corpus. (2) To analyze the humanistic vision that underlies and unifies these themes, situating it within both Islamic and contemporary sociological frameworks. (3) To assess the theoretical and practical significance of al-Sadr's social integration model for contemporary scholarship and for Muslim communities facing comparable challenges of fragmentation and marginalization.

METHODOLOGY

This study applies qualitative thematic analysis to the corpus of forty-five Friday sermons delivered by al-Sadr during 1418–1419 AH (1997–1999 CE). Following the procedure established by Braun and Clarke (2006), the analysis proceeds through six phases: familiarization with the data, initial coding, searching for themes, reviewing themes, defining and naming themes, and producing the final analytical account. The analysis focuses specifically on passages addressing social relations, communal obligations, collective identity, and the conditions of community life, identifying sixteen thematic categories of social integration discourse across the corpus. The study treats the sermon corpus as both a textual object (to be analyzed for its propositional content) and a social performance (to be analyzed for the social relationships it enacts). This dual analytical orientation is essential to capturing the full dimensions of al-Sadr's social integration vision.

RESULTS

Sixteen Thematic Categories Of Social Integration: Systematic analysis of the forty-five sermons identifies sixteen recurrent and interconnected thematic categories through which al-Sadr constructs and advocates his vision of social integration. These are presented below in order of their frequency and centrality in the corpus. (1) Congregational Prayer as Social Practice (al-Salāt al-Jamāʿiyya): The most

frequently recurring social integration theme across the corpus, appearing in all forty-five sermons, is the obligation and practice of congregational prayer. Al-Sadr's argument for Friday and congregational prayer is not primarily legal (though it has a legal dimension) but social: gathering in prayer is, for al-Sadr, the foundational act through which community is constituted, identity is affirmed, and solidarity is renewed. The very act of standing shoulder-to-shoulder in prayer embodies the equality, unity, and mutual recognition that al-Sadr places at the heart of his social vision. His insistence on large congregational prayer in the face of regime surveillance was simultaneously a spiritual act and a social one, a weekly reaffirmation of community in defiance of enforced atomization. (2) Religious Authority and Community Guidance (al-Marja'iyya al-Mujtamaʿiyya): Al-Sadr consistently frames the relationship between the marjaʿ (supreme religious authority) and the community not in terms of hierarchical legal obligation but in terms of mutual care, responsibility, and service. The marjaʿ in the Sadrist vision is not a distant scholarly authority to whom legal questions are submitted; he is a communal shepherd (rāʿī) who must live among, know, and respond to the concrete needs of his community. This relational model of religious authority is a direct expression of al-Sadr's social integration vision: authority is legitimate only when it is embedded in and accountable to the social fabric it claims to serve. (3) Social Solidarity and Mutual Support (al-Takāful al-Ijtimāʿī): Across thirty-nine sermons, al-Sadr addresses the theme of social solidarity directly, calling on community members to support one another materially, emotionally, and spiritually. His treatment of this theme goes beyond conventional charitable exhortation: he analyzes the structural conditions that produce poverty and social vulnerability, links individual obligation to collective responsibility, and argues that a community that tolerates extreme inequality within its ranks has failed its own foundational values. (4) Communal Identity and Belonging (al-Huwiyya al-Jamāʿiyya): Al-Sadr devotes significant attention in thirty-five sermons to the question of identity, what it means to belong to a community, what shared values and practices constitute membership, and how communal identity can be maintained and strengthened under conditions of external pressure and internal fragmentation. His treatment is notably inclusive: he resists sectarian narrowness and emphasizes the universal human dimensions of Islamic communal identity while defending its particular historical and cultural expressions. (5) The Role of Youth in Social Renewal (Dawr al-Shabāb): In thirty-two sermons, al-Sadr addresses the younger generation directly,

assigning them a central role in his social integration vision. He speaks to them not as objects of moral instruction but as subjects of social agency, as the primary bearers of the community's capacity for renewal and transformation. This orientation toward youth as social actors rather than social problems is a distinctive feature of the Sadrist humanistic vision. (6) Education and Knowledge as Social Goods (al-ʿIlm wa al-Tarbiyya): Al-Sadr treats knowledge and education in twenty-nine sermons not merely as individual achievements but as shared social resources whose production and distribution are matters of communal obligation. His insistence on making complex knowledge accessible to the widest possible audience, enacted through the methodology of the sermons themselves, is itself a social integration practice: it dissolves the knowledge hierarchies that divide scholarly elites from popular communities and insists on the intellectual dignity of every community member. (7) Family as the Foundation of Social Integration (al-Usra wa al-Mujtamaʿ): The family unit appears in twenty-seven sermons as the primary social institution through which the values of solidarity, care, mutual recognition, and shared identity are first learned and practiced. Al-Sadr's treatment of the family is notably sociological: he analyzes the conditions under which families are strengthened or weakened, links family health to broader social conditions, and addresses the specific vulnerabilities faced by families under the economic and political pressures of the time. (8) Mosques as Centers of Social Life (al-Masjid ka Markaz Ijtimāʿī): In twenty-five sermons, al-Sadr explicitly advocates for the mosque as a comprehensive social center, not merely a site of ritual worship but a space for education, dispute resolution, community organization, mutual support, and collective deliberation. This vision of the mosque as a social integration institution draws on historical precedents in early Islamic society while responding directly to the conditions of contemporary Iraqi community life, where other civil society institutions had been systematically destroyed by the regime. (9) Social Justice and Equity (al-ʿAdāla al-Ijtimāʿiyya): Twenty-three sermons address questions of social justice directly, with al-Sadr linking the condition of social integration to the distribution of material resources and social opportunities. A community cannot be genuinely integrated, in his analysis, if significant portions of its members are excluded from basic economic security, access to education, or social recognition. His treatment of social justice is not abstract: he addresses specific conditions of poverty, unemployment, and economic marginalization in his congregation's lived experience. (10) Civic Responsibility and Public Ethics (al-

Mas'ūliyya al-ʿĀmma): Twenty sermons treat the theme of civic responsibility, the obligations that community members bear not only to their immediate families and social networks but to the wider public community. Al-Sadr's concept of civic responsibility is grounded in the Islamic concept of amr bi al-maʿrūf wa nahy ʿan al-munkar but extends it into a comprehensive social ethics that governs behavior in markets, streets, public spaces, and institutions. (11) Resistance to Social Fragmentation (Muqāwamat al-Tafakkuk): Nineteen sermons explicitly address the forces and dynamics that produce social fragmentation, tribalism, sectarianism, personal rivalry, political division, and the social effects of poverty and humiliation. Al-Sadr analyzes these fragmenting forces with sociological precision and argues for specific practices and attitudes that can resist them and maintain communal cohesion. (12) Dignity and Self-Respect as Social Values (al-Karāma wa al-Iʿtizāz): Seventeen sermons address the theme of human dignity (karāma) as a foundational social value. Al-Sadr's treatment of dignity is notably egalitarian: every human being possesses inherent dignity regardless of social status, economic position, or level of religious learning. This insistence on universal human dignity underpins his social integration vision by establishing a moral foundation for the equal worth of every community member. (13) Dialogue and Reconciliation (al-Ḥiwār wa al-Muṣālaḥa): Sixteen sermons address the theme of internal community dialogue and reconciliation, the processes through which conflicts are resolved, divisions are healed, and unity is maintained without suppressing legitimate disagreement. Al-Sadr's model of community dialogue is notably mature: he does not call for the elimination of difference but for its constructive management through principled, mutually respectful argument. (14) Women's Role in Social Integration (Dawr al-Mar'a): Fourteen sermons address the role of women in community life and social integration, with al-Sadr taking positions that were progressive within his context, affirming women's full membership in the religious community, their capacity for religious knowledge, and their essential contribution to both family and public social life. (15) Relationship with the Other (al-ʿAlāqa maʿa al-Ākhar): Twelve sermons address the community's relationship with those outside it, non-Shia Muslims, non-Muslims, and those who hold different political or social positions. Al-Sadr's treatment of the Other is consistently guided by principles of justice, fairness, and shared humanity, refusing the logic of pure communal exclusivity while maintaining the integrity of the community's own identity and values. (16) A Model Friday Sermon: The culminating section of the corpus, sermons numbered 42

through 45, delivered in the final months before al-Sadr's martyrdom in February 1999, represents the fullest and most integrated expression of his social vision. These sermons synthesize all the thematic strands identified above into a comprehensive humanistic program for community renewal, addressing simultaneously the spiritual, social, economic, and political dimensions of the community's condition with extraordinary depth and coherence.

DISCUSSION

1. Interpreting the Findings: Integration as a Deliberate Social Project: The results indicate that Muhammad Muhammad Sadiq al-Sadr's Friday sermons (1997–1999) present social integration not as a secondary moral theme but as an organizing logic that structures the sermonic corpus as a whole. The sixteen thematic categories identified through coding, ranging from congregational prayer and communal identity to civic ethics, dignity, and reconciliation, form a coherent social vision aimed at repairing the fragmented lifeworld of Iraqi Shi'i society under late Ba'thist repression. In sociological terms, the sermons function as a continuous intervention against anomie, distrust, and enforced social atomization. This supports the paper's central claim that the sermon series should be read as a sustained "social engineering" effort, though one anchored in religious ethics rather than state technocracy. What makes this project distinctive is that al-Sadr does not treat integration as mere conformity or obedience. Instead, integration is framed as belonging with obligations: the individual joins the community not by passive identification, but by participating in shared practices (prayer, mutual support), shared norms (public ethics), and shared responsibilities (enjoining good and forbidding evil). Thus, "integration" is simultaneously spiritual (worship), moral (virtue), relational (solidarity), and civic (public responsibility). This layered conception allows al-Sadr's discourse to operate as a bridge between classical Islamic moral vocabulary and modern sociological concerns.

2. Social Performance and the Sermon as Institution: A key implication of the methodology, treating the sermons as both text and performance, is that integration is enacted, not only described. The weekly gathering itself becomes a ritualized production of community. Al-Sadr's insistence on large congregational prayers, delivered publicly in Kufa under surveillance, can be read as a practice of

collective visibility that reconstitutes social bonds. In Durkheimian terms, Friday prayer serves as a recurring "social fact" that regenerates collective conscience and solidarity through embodied co-presence. The shoulder-to-shoulder formation and synchronized action become a lived pedagogy of equality and mutual recognition. This performative dimension helps explain why congregational prayer appears across all forty-five sermons and dominates the corpus. Al-Sadr's argument is not only that prayer is obligatory; it is that prayer is community-making. The sermon platform, often the only mass forum still available in a society where civil associations were crushed, substitutes for the missing institutions of civil society. The mosque, as he repeatedly stresses, is not merely a worship site but a multi-purpose civic space: education, dispute resolution, welfare coordination, and moral deliberation. In contemporary sociological language, al-Sadr was reactivating an institution capable of generating dense networks of trust, i.e., social capital, when other network-generating institutions had been destroyed.

3. Social Capital: Bonding, Bridging, and Controlled Openness: The findings align strongly with Putnam's framework of social capital, particularly the distinction between bonding and bridging ties. Many themes, mutual support (takāful), communal identity, family strengthening, youth activation, clearly cultivate bonding capital within the Shi'i community, reinforcing internal solidarity as a defense against repression, poverty, and humiliation. However, the corpus also contains repeated gestures toward bridging dynamics: relationship with the Other, fairness, justice, civic responsibility, and non-sectarian conceptions of dignity and public ethics. These themes indicate that al-Sadr's model was not designed solely to thicken internal identity, but also to protect the community from the pathologies of inward closure (tribalism, factional rivalry, sectarian withdrawal). Importantly, bridging in this model is not a naïve universalism. It is principled openness: the community remains anchored in its ethical and theological commitments while extending justice and recognition outward. This matters analytically because it complicates common portrayals of late-1990s Shi'i revival as necessarily sectarian. Instead, the sermons suggest a more nuanced integration strategy: build internal cohesion to survive, while maintaining a moral grammar that resists dehumanization of outsiders. That approach is consistent with humanistic sociology's emphasis on recognition and dignity as prerequisites for stable social life.

4. Human Dignity as a Foundational Integrative Value: One of the most theoretically significant findings is the prominence of dignity (karāma) as a recurring value. In many modern sociological and philosophical accounts, dignity is treated as an abstract normative principle; in al-Sadr's sermons it is operationalized as a social glue. Dignity is the basis for equal standing, which is in turn required for authentic solidarity. Without dignity, charity becomes humiliation, authority becomes domination, and identity becomes exclusion. The sermons' insistence that every person possesses inherent worth, regardless of social status, economic position, or level of religious learning, provides a moral infrastructure for integration. This is where the paper's claim about "Islamic humanism" becomes especially persuasive: al-Sadr's discourse repeatedly links religious obligation to the protection of the human person as such, not merely the maintenance of ritual compliance. This is also why themes like education as a shared good and youth as agents (not problems) fit coherently into the larger model: dignity entails intellectual and social agency, not just material survival.

5. Authority Reimagined: From Juridical Distance to Communal Shepherding: The category "religious authority and community guidance" is central for understanding how integration is to be sustained over time. In al-Sadr's model, the marjaʿ is not a remote legal specialist but a socially embedded guide responsible for the lived condition of the community. This is a major departure from a minimalist model of authority where scholars answer questions when asked. Instead, authority is legitimized by proximity, accountability, and service, what the paper aptly calls "communal shepherding." Sociologically, this reconfiguration has two effects. First, it personalizes trust: in a context of state terror and societal suspicion, trust is rebuilt through embodied leadership that shares the risks of the community. Second, it creates an ethical hierarchy that competes with the state's coercive hierarchy. Under authoritarian conditions, such parallel moral authority can become a powerful mechanism of social coordination and resilience. At the same time, this form of authority can generate ambiguity: it may enable empowerment and protection, but it also concentrates symbolic power in the figure of the religious leader, which can later be translated into political power. This ambiguity does not undermine the integration project, but it helps explain how a religious integration platform can become a foundation for subsequent mass mobilization.

6. Civic Ethics and the Extension of "Integration" Beyond the Mosque: The results show that al-Sadr consistently extends the integration agenda into everyday public life, markets, streets, institutions, through the theme of civic responsibility and public ethics. By grounding civic responsibility in amr bi al-maʿrūf wa nahy ʿan al-munkar, he transforms a familiar Islamic concept into a broad social ethic: honesty in transactions, restraint in conflict, care for public order, and refusal of corruption-like behaviors. Integration here is not only emotional belonging; it is norm-governed participation in shared public spaces. This framing is crucial because it positions social integration as a proto-civic project under conditions where the state had lost legitimacy. The sermons become a moral curriculum for "citizenship without a democratic state," teaching practices of mutual obligation and public-minded behavior even while the political system remained authoritarian. That helps explain the paper's conclusion that the sermon corpus resembles a program of social reconstruction: it supplies norms and institutional imaginaries (mosque-as-community-center, family-as-training-ground, knowledge-as-public-good) that allow society to hold together when formal politics is predatory.

7. Managing Fragmentation: Conflict, Reconciliation, and Social Repair: The categories of resistance to fragmentation and dialogue/reconciliation point to a sophisticated awareness of internal community vulnerabilities. Al-Sadr identifies tribalism, rivalry, poverty-induced resentment, and social humiliation as forces that dissolve cohesion from within. Rather than denying conflict, the sermons propose mechanisms for managing it: dialogue, reconciliation, and principled argument. This aligns with contemporary cohesion research emphasizing that durable integration does not require homogeneity; it requires institutions and norms capable of handling difference without escalation. Notably, the reconciliation theme complements the dignity theme. Reconciliation is not framed as mere quietism; it is framed as a moral discipline that protects the social fabric. This is a non-trivial point in contexts of repression, where communities often oscillate between fear-driven silence and anger-driven fracture. By proposing reconciliation as an active practice, the sermons provide tools for social repair.

8. Gender, Family, and Youth: Reproduction of Community Across Generations: Three findings together, family, women's role, and youth, show that al-Sadr's integration model is generationally oriented. Integration is not treated as a one-time mobilization; it must be reproduced through institutions

of socialization. The family is portrayed as the primary site where solidarity, care, and identity are learned; women are framed as essential participants in religious community life; youth are addressed as carriers of renewal and agency. This combination suggests a theory of social continuity: a community survives authoritarian pressure by investing in the reproduction of values, knowledge, and public ethics across generations. Analytically, this also helps explain why education and knowledge are not peripheral in the corpus. Knowledge is a social good because it prevents dependency and passivity; it gives community members the capacity to deliberate, to recognize manipulation, and to participate meaningfully. Thus, education in the sermons is not only piety-oriented; it is integration-oriented.

9. The Late Sermons as Synthesis: Toward a "Complete" Integration Model: Your findings note that sermons 42–45 represent the most integrated articulation of the project. Interpreting this, one can argue that al-Sadr's discourse evolves from repeated emphasis on foundational practices (prayer, solidarity, mosque centrality) toward a more explicit synthesis of spiritual, ethical, social, and public dimensions. This implies that the sermonic corpus is developmental: it builds a community's capacities step by step. Such a reading strengthens the argument that this is not an accidental set of topics but a strategic program unfolding over time.

10. Theoretical Contribution and Broader Implications

Placing these results within sociological theory, the study contributes in two directions. First, it demonstrates that a religious sermonic corpus can function as a dense site of sociological theorizing about cohesion, solidarity, and community repair, without adopting the vocabulary of modern sociology. Second, it shows that "humanistic sociology" is not exclusively a secular tradition: al-Sadr's integration model anticipates humanistic concerns (recognition, meaning, dignity, belonging) while embedding them in Islamic moral and theological commitments. For contemporary scholarship, this matters because it challenges binaries that oppose "religious discourse" to "social theory." The sermons are at once theology and sociology-in-practice: they diagnose social breakdown, propose institutional remedies, and mobilize collective participation. For contemporary communities facing fragmentation, whether from authoritarianism, war, sanctions, or social inequality, the Sadrist model offers a case of how moral

language, ritual practice, and communal institutions can be assembled into a coherent integration strategy.

11. Limitations and a Note on Interpretation: While the thematic mapping provides strong evidence of a coherent integration vision, the study's textual focus limits the ability to measure reception: how different audiences internalized these themes, and whether the sermons' integrative aspirations were realized unevenly across class, gender, or locality. Future work could pair this textual map with oral histories, ethnographic observation of mosque-centered networks, or discourse analysis comparing sermon themes with later grassroots practices. Such research would clarify the mechanisms by which sermonic integration becomes social behavior, and where the project encounters resistance, reinterpretation, or unintended consequences.

Concluding Synthesis: Overall, the discussion supports the claim that Muhammad al-Sadr's Friday sermons constitute a systematic humanistic vision of social integration under conditions of social collapse. The sixteen thematic categories form an internally coherent model in which ritual practices generate solidarity, authority is re-embedded in communal care, dignity grounds equality, education enables agency, and civic ethics extend integration into public life. The sermons therefore emerge as both a moral discourse and a pragmatic strategy for rebuilding community, an approach that remains analytically valuable for understanding religiously grounded social cohesion projects in fragile and post-conflict societies.

CONCLUSION

This study has sought to reconstruct the intellectual and social architecture of Muhammad al-Sadr's forty-five Friday sermons, delivered in the Kufa mosque between 1997 and 1999. By moving beyond a purely theological or liturgical reading, this paper has demonstrated that the sermon corpus constitutes a deliberate and systematic program of social engineering. At a moment when the Iraqi social fabric was being systematically dismantled by authoritarian repression, economic sanctions, and forced isolation, al-Sadr utilized the sermon platform to launch a comprehensive project of communal renewal. The

resulting vision, what this paper has categorized as a "Sadrist humanistic vision of social integration", stands as a significant contribution to both Islamic thought and contemporary sociological inquiry.

The primary finding of this research is that social integration in the Sadrist model is not a peripheral concern or an abstract moral aspiration; it is the fundamental logic that organizes the community's identity, practices, and civic life. Through the thematic mapping of sixteen recurring categories, from the performative power of congregational prayer to the reimagining of religious authority as "communal shepherding," and the elevation of dignity (karāma) as a foundational social value, the corpus reveals a coherent logic of cohesion. Al-Sadr's vision refuses the atomization of the individual, opting instead for a human person who finds fulfillment and meaning only through participation in a wider, morally governed community.

Crucially, this vision is demonstrably humanistic. By situating al-Sadr's model within the frameworks of humanistic sociology, this paper has highlighted a striking convergence between his Islamic ethical prescriptions and modern concerns regarding belonging, recognition, and social capital. Al-Sadr did not view the community as a structure to be commanded, but as an organism to be nurtured. His insistence on the centrality of youth as agents of renewal, the mosque as a multipurpose civic institution, and dialogue as a disciplined practice for resolving internal conflict, reveals a sophisticated awareness of the institutional requirements for sustaining social life under duress. His model rejects the "totalitarian" impulse of state control in favor of the "associational" impulse of civil society, an irony of history, given that his sermons operated within a state that sought to eliminate all such associations.

Theoretically, the significance of this study lies in its bridge-building between distinct intellectual traditions. By demonstrating how al-Sadr operationalized classical Islamic concepts, such as ukhuwwa (brotherhood), taʿāwun (mutual assistance), and amr bi al-maʿrūf (public ethics), he effectively created a "sociology of the sacred." He showed that one could derive a robust, modern-facing theory of social integration directly from the theological foundations of the faith. This challenges the persistent secular-liberal bias in sociological research, which often struggles to categorize the social work of religious

movements as anything other than "fundamentalist" or "reactionary." Al-Sadr's sermons, by contrast, offer a template for a progressive, inclusive, and socially responsible religious public sphere.

The legacy of this humanistic vision is complex. As the paper has suggested, the concepts developed in the late 1990s did not remain contained within the Kufa mosque; they became the "conceptual DNA" of the subsequent Sadrist movement. However, the migration of these ideas into the competitive, volatile landscape of post-2003 Iraqi politics has been fraught with tension. The transition from a "theology of resistance and solidarity" to a "politics of governance and institutional power" inevitably tests the purity of the original vision. The study of how these integrationist ideals, such as the rejection of corruption, the focus on the poor, and the call for public ethics, are negotiated when the movement itself becomes a stakeholder in state power, remains one of the most critical areas for future inquiry.

Finally, this paper serves as an invitation to further scholarly exploration. While this textual analysis has mapped the thematic terrain of the sermons, there remains a need for empirical, ethnographic research into the "reception history" of these ideas. How do the various constituencies of the Sadrist movement, across different generations, social classes, and political contexts, interpret the call to "social integration" in their daily lives? To what extent do the practices of the 1990s persist in the grassroots organization of the movement today? These questions are essential for understanding the durability of al-Sadr's intellectual project.

In conclusion, Muhammad al-Sadr's Friday sermons remain a profound testament to the power of religious discourse to act as a source of social resilience. He transformed the mosque into a laboratory for community-building and the sermon into a curriculum for civic life. His humanistic vision of integration, anchored in the inherent dignity of the individual and the mutual obligation of the community, remains not only a historical artifact of Iraqi resistance but a vital case study for any student of Islamic social movements. It teaches us that even in the most fractured and isolated environments, the human impulse toward solidarity, if guided by a clear moral grammar and institutional imagination, can succeed in rebuilding a world.

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TAX EVASION IN THE CONSTRUCTION SECTOR AND ITS EFFECTA ON THE PUBLIC BUDGET

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Abstract

Tax evasion is widely regarded as one of the most serious forms of economic crime, with a particularly strong negative impact on public finances. This issue is especially prevalent in sectors marked by a high degree of informality, such as the construction industry. The present study examines the scope and characteristics of tax evasion within the construction sector of the Republic of Moldova, with a specific focus on its repercussions for the state budget. It explores the various methods through which tax obligations are circumvented, as well as the underlying structural factors that enable the persistence of such practices over time.

Furthermore, the analysis addresses both the economic and social implications of tax evasion, emphasizing its broader consequences beyond immediate fiscal losses. The results indicate that tax evasion in the construction sector leads to significant reductions in public revenue, thereby limiting the government's capacity to finance essential services and infrastructure projects. In addition, it creates an uneven competitive environment by offering illicit advantages to non-compliant entities, ultimately discouraging fair business practices. Over time, these effects contribute to the weakening of sustainable economic development and undermine trust in public institutions and regulatory frameworks.

Keywords: tax evasion, construction sector, public budget, shadow econom, mechanisms of tax evasion.

İNŞAAT SEKTÖRÜNDE VERGİ KAÇAKÇILIĞI VE KAMU BÜTÇESİ ÜZERİNDEKİ ETKİLERİ

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Özet

Vergi kaçakçılığı, kamu maliyesi üzerinde özellikle güçlü olumsuz etkiler yaratan en ciddi ekonomik suç türlerinden biri olarak kabul edilmektedir. Bu sorun, özellikle inşaat sektörü gibi kayıt dışılığın yüksek olduğu alanlarda daha yaygın şekilde görülmektedir. Bu çalışma, Moldova Cumhuriyeti'nde inşaat sektöründeki vergi kaçakçılığının kapsamını ve temel özelliklerini incelemekte, özellikle de devlet bütçesi üzerindeki etkilerine odaklanmaktadır. Araştırma, vergi yükümlülüklerinden kaçınmak için kullanılan çeşitli yöntemleri ve bu tür uygulamaların zaman içinde devam etmesine olanak tanıyan yapısal faktörleri analiz etmektedir.

Bunun yanı sıra, çalışma vergi kaçakçılığının ekonomik ve sosyal boyutlarını da ele almakta, yalnızca doğrudan mali kayıplarla sınırlı kalmayan daha geniş etkilerini vurgulamaktadır. Elde edilen bulgular, inşaat sektöründeki vergi kaçakçılığının kamu gelirlerinde önemli azalmalara yol açtığını ve bunun da devletin temel kamu hizmetleri ile altyapı projelerini finanse etme kapasitesini sınırladığını göstermektedir. Ayrıca bu durum, yasal yükümlülüklerini yerine getirmeyen aktörlere haksız avantajlar sağlayarak rekabet ortamını bozmakta ve adil ticari uygulamaları zayıflatmaktadır. Uzun vadede, bu etkiler sürdürülebilir ekonomik kalkınmayı olumsuz yönde etkilemekte ve kamu kurumlarına ile düzenleyici çerçevelere olan güveni azaltmaktadır.

Anahtar Kelimeler: vergi kaçakçılığı, inşaat sektörü, kamu bütçesi, kayıt dışı ekonomi, vergi kaçakçılığı mekanizmaları.

1. Introduction

Tax evasion can be described as an intentional and illicit form of conduct whereby natural or legal persons deliberately seek to circumvent their fiscal duties owed to the state. This behavior is not accidental but rather involves a conscious decision to violate tax legislation in order to obtain financial benefits. In practice, it typically manifests through the concealment, manipulation, or misrepresentation of financial data, with the purpose of minimizing the amount of taxes due. Common methods include the underreporting of income, the omission of certain transactions from official records, or the use of falsified accounting documents to create an inaccurate picture of a taxpayer's real financial situation.

Within the Republic of Moldova, tax evasion represents a persistent and widespread challenge, particularly in branches of the economy where informal activities are deeply rooted. Sectors with limited regulatory oversight and a high reliance on cash transactions are especially vulnerable to such practices. Among these, the construction industry stands out as a prominent example, given its structural characteristics, including the frequent use of undeclared labor, subcontracting chains, and fluctuating project-based activities. These conditions create an environment conducive to tax evasion, making effective monitoring and enforcement significantly more difficult for public authorities (Luchian & Tepordei, 2018).

In this framework, tax evasion most often manifests through the partial or complete omission of taxable income from official declarations, meaning that individuals or companies deliberately fail to report their real earnings to the fiscal authorities. Such practices have a direct and measurable impact on public finances, as they lead to a significant reduction in budgetary revenues. Consequently, the state's capacity to allocate sufficient resources for essential public functions such as healthcare, education, social protection, and infrastructure development is substantially weakened. Over time, these deficits can affect not only the quality of public services but also the overall efficiency and sustainability of governmental policies.

At the same time, undeclared work represents a closely related and highly prevalent phenomenon, particularly in the construction sector. This type of activity involves remunerated labor that is intentionally not reported to the competent public institutions, thereby bypassing taxation and social security contributions. As a result, the state is deprived not only of tax income but also of funds necessary for social insurance systems. Beyond the fiscal implications, undeclared work also generates significant social risks, as workers engaged in such

arrangements are often left without legal protection, employment rights, or access to benefits such as healthcare, pensions, and unemployment support.

2. Characteristics of Tax Evasion in the Construction Sector

In the Republic of Moldova, tax evasion within the construction sector takes on a variety of concrete and recurrent forms, reflecting both the structural vulnerabilities of the industry and the persistence of informal economic practices. One of the most common methods involves the systematic underreporting of revenues, whereby companies intentionally declare lower earnings than those actually obtained. This is often accompanied by the concealment of genuine financial transactions, allowing economic operators to reduce their taxable base and, consequently, their fiscal obligations.

Another widespread practice consists in the use of parallel or "*off-the-books*" accounting systems. Through such mechanisms, businesses maintain unofficial records that are not disclosed to tax authorities, enabling them to evade the payment of value-added tax (VAT) and corporate income tax. In addition, informal employment remains a defining characteristic of the sector. Workers are frequently hired without formal contracts, and wages are partially or entirely paid "*in envelopes*," meaning they are not declared to fiscal or social security institutions. This practice not only reduces tax contributions but also deprives employees of legal protections and social benefits.

Furthermore, tax evasion schemes often involve fictitious transactions and the issuance of false invoices, particularly in relation to the procurement of construction materials. These artificial operations are designed to inflate expenses or justify non-existent activities, thereby further diminishing taxable profits.

The magnitude of this phenomenon is illustrated by recent enforcement actions. Investigations conducted by Moldovan authorities have revealed complex tax evasion schemes in the construction sector, with estimated damages reaching approximately 7–8 million MDL. These cases typically involve undeclared income and deliberate strategies aimed at circumventing fiscal obligations, highlighting both the scale and the sophistication of such illicit practices (RM Moldova, 2026).

In more sophisticated instances of tax evasion, companies resort to elaborate schemes involving artificially constructed supply chains and entirely fictitious commercial transactions. These arrangements are designed to create the appearance of legitimate business activity while, in reality, masking the absence of genuine economic operations. By inserting intermediary

entities often shell companies with no real operational capacity into the transaction flow, businesses are able to manipulate invoices, inflate expenses, and obscure the true origin and destination of funds.

Such fraudulent mechanisms allow companies to significantly reduce their taxable income and avoid the payment of value-added tax and corporate taxes. In many cases, these fictitious transactions are supported by fabricated documentation, making detection more difficult for fiscal authorities and complicating the audit process.

The scale of these schemes can be considerable, as evidenced by investigations revealing tax evasion amounts exceeding 40 million MDL. These figures underscore not only the financial impact on the state budget but also the increasing level of sophistication and organization involved in such illicit practices within the construction sector.

3. Causes of Tax Evasion in Construction

A range of deeply rooted structural and institutional determinants explain why tax evasion continues to persist in the construction sector, particularly in the Republic of Moldova. These factors are interconnected and collectively create an environment in which non-compliance becomes both feasible and, in some cases, economically advantageous.

One of the primary drivers is the extensive presence of the informal economy within the construction industry. This sector is widely recognized as a major contributor to undeclared economic activity, where a significant proportion of work is carried out without formal registration or legal oversight. Informal employment arrangements, unreported transactions, and the absence of proper documentation facilitate the concealment of income and the avoidance of tax obligations. The project-based and fragmented nature of construction activities further complicates monitoring, making it easier for operators to function outside the formal regulatory framework.

Another important factor relates to deficiencies within the regulatory and administrative system. Frequent amendments to tax and construction-related legislation can create uncertainty and loopholes that are exploited by economic actors. At the same time, bureaucratic inefficiencies, limited institutional coordination, and insufficiently developed control mechanisms weaken the capacity of authorities to detect and prevent tax evasion. These shortcomings reduce the overall effectiveness of fiscal oversight and enforcement.

Economic considerations also play a significant role in encouraging tax evasion. High tax rates, combined with substantial compliance costs, may push businesses especially small and medium-sized enterprises to seek alternative, often illegal, ways of reducing their financial

burden. In a competitive market environment, some firms perceive tax evasion as a strategy for maintaining profitability and gaining a competitive edge over compliant competitors.

Finally, corruption and limited enforcement capacity significantly undermine efforts to combat tax evasion. When public officials lack integrity or when oversight institutions are under-resourced, the risk of detection and sanctioning decreases considerably. This, in turn, emboldens businesses to continue engaging in illicit practices, as the perceived costs of non-compliance remain low. The combination of weak enforcement and corrupt practices thus perpetuates a cycle in which tax evasion becomes entrenched within the sector.

4. Impact on the Public Budget

Tax evasion has a profound and direct impact on the level of public revenues collected by the state. By deliberately concealing income or engaging in undeclared economic activities, individuals and companies significantly diminish the tax base. In the Republic of Moldova, estimates suggest that the informal economy generates annual losses to the state budget of approximately 15 billion MDL, with a considerable share attributable to sectors such as construction, where informal practices are particularly widespread (IPN Press Agency, 2021). These substantial financial losses weaken the overall fiscal capacity of the state, limiting its ability to ensure stable and sufficient revenue streams. As a result, the government faces increasing difficulties in allocating adequate resources for essential public expenditures, including the provision of basic services, the development of infrastructure, and the implementation of social support programs.

Another critical consequence of tax evasion is the distortion it introduces into the competitive environment. Businesses that evade taxes benefit from reduced operational costs, enabling them to offer lower prices or achieve higher profit margins compared to law-abiding competitors. This creates an uneven playing field, where compliant firms are placed at a disadvantage and may struggle to remain competitive. Over time, such conditions discourage fair competition, incentivize further non-compliance, and erode the principles of transparency and integrity that are essential for a healthy market economy.

The decline in budgetary revenues caused by tax evasion also has significant implications for public investment. With fewer financial resources at its disposal, the state is constrained in its ability to fund infrastructure projects, including the construction and maintenance of roads, housing, and public utilities. This situation is particularly paradoxical in the case of the construction sector, which both contributes to and suffers from the consequences of tax evasion.

Insufficient investment in infrastructure can hinder economic growth, reduce the quality of public services, and delay modernization efforts.

Beyond its fiscal and economic effects, tax evasion also generates serious social consequences. By reducing the funds available for critical sectors such as healthcare, education, and social protection, it negatively affects the overall standard of living of the population. Moreover, it exacerbates social inequalities, as the burden of financing public goods shifts disproportionately onto compliant taxpayers. In the long term, persistent tax evasion undermines public confidence in state institutions and weakens the perceived legitimacy of the legal and fiscal system, thereby contributing to a cycle of reduced compliance and institutional fragility.

5. Case Studies and Practical Implications

Recent criminal investigations conducted in the Republic of Moldova provide clear and concrete evidence of how tax evasion operates in practice, particularly within the construction sector. These cases reveal not only the existence of illegal fiscal practices but also the ways in which financial resources that should have been allocated to the public budget are instead diverted for private gain.

In several instances, construction companies have been implicated in complex schemes designed to avoid the payment of taxes owed to the state. Rather than fulfilling their fiscal obligations, these entities deliberately withheld tax payments and subsequently redirected the retained funds toward the acquisition of private real estate assets. Such practices involve the intentional misallocation of financial resources, where money that legally belongs to the state is used to finance investments that benefit the company or its affiliates.

This form of tax evasion illustrates a dual impact: on the one hand, it deprives the public budget of essential revenues needed to support public services and infrastructure, and on the other hand, it enables the accumulation of private wealth through illicit means. Moreover, these schemes often involve sophisticated financial arrangements and the use of intermediary entities, making detection and prosecution more challenging for authorities. Overall, these cases highlight both the scale and the tangible consequences of tax evasion in the construction industry (M1Moldova, 2025).

Law enforcement and fiscal authorities have uncovered a series of coordinated and well-structured schemes centered on the provision of undeclared services and the systematic concealment of revenues. These arrangements were not isolated incidents but rather organized operations in which economic activities were intentionally kept outside the official reporting system. Companies involved in such practices deliberately failed to record the full extent of

their services and income, thereby avoiding taxation and depriving the state of significant financial resources. As a consequence, the national treasury has suffered considerable losses, reflecting the cumulative impact of these illicit activities over time.

These documented cases provide compelling evidence of both the magnitude and the level of complexity associated with tax evasion in the construction sector. On the one hand, the financial damage highlights the large scale at which such practices are carried out, often involving substantial sums of money. On the other hand, the structured nature of these schemes frequently involving multiple actors, layered transactions, and deliberate concealment strategies demonstrates a high degree of sophistication. Together, these elements underscore the serious challenges faced by authorities in detecting, investigating, and effectively combating tax evasion within this industry (RM Moldova, 2026).

6. Measures to Combat Tax Evasion

In order to effectively combat and mitigate the persistence of tax evasion, a comprehensive and multi-dimensional set of policy interventions is required, targeting both its underlying causes and its practical manifestations. First and foremost, it is essential to reinforce fiscal control and auditing mechanisms by improving the capacity, resources, and coordination of supervisory institutions. Strengthened inspection procedures and risk-based audits can significantly enhance the detection of irregularities and deter non-compliant behavior.

Equally important is the digitalization of tax administration systems, which can play a crucial role in increasing transparency and efficiency. The implementation of electronic reporting, real-time data exchange, and integrated information platforms can reduce opportunities for manipulation and facilitate more accurate monitoring of financial activities.

Another key measure involves addressing the high level of informality, particularly in the labor market. Structural reforms aimed at encouraging formal employment such as simplifying registration procedures, reducing administrative burdens, and offering incentives for compliance can help bring economic activities into the legal framework.

Furthermore, strengthening the legal framework by introducing more effective and proportionate sanctions, alongside enhancing the enforcement capacity of competent authorities, is vital for ensuring accountability. A credible system of penalties increases the perceived risks associated with tax evasion.

Finally, promoting voluntary compliance should not be overlooked. Educational initiatives, awareness campaigns, and incentive-based approaches can foster a culture of tax responsibility, encouraging individuals and businesses to comply with fiscal obligations not only out of fear of sanctions but also as a matter of civic duty.

7. Conclusion

Tax evasion within the construction sector constitutes a serious and persistent challenge for the Republic of Moldova, generating wide-ranging consequences for both the stability of the public budget and the broader trajectory of economic development. This phenomenon is not incidental but rather deeply rooted in structural conditions, including the high prevalence of informal economic activities, limited effectiveness of enforcement mechanisms, and ongoing financial pressures faced by businesses operating in a competitive environment. Together, these factors create a context in which non-compliance becomes both feasible and, for some actors, economically attractive.

The repercussions of tax evasion are extensive and multifaceted. On a fiscal level, it leads to considerable losses in public revenue, thereby constraining the state's ability to finance essential services and strategic investments. At the same time, it distorts market dynamics by granting unfair advantages to those who evade their obligations, undermining fair competition and discouraging compliant behavior. Moreover, reduced budgetary resources translate into limited public investment capacity, particularly in infrastructure and development projects, which are crucial for economic progress.

Effectively addressing this issue requires a coordinated and comprehensive strategy that integrates legal reforms, institutional strengthening, and the adoption of modern technological solutions. Enhancing regulatory frameworks, improving enforcement efficiency, and expanding digital tools for monitoring and compliance are all essential components of such an approach.

In the long term, curbing tax evasion in the construction sector is fundamental for ensuring fiscal sustainability, reinforcing the rule of law, and fostering sustainable economic growth in the Republic of Moldova.

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