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Proceedings of

International Conference

Date: 09-10 July 2026

Venue: Hong Kong



Proceedings of
INTERNATIONAL CONFERENCE
HONG KONG

Date of Event: 09th – 10th July, 2026

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Address: IFZA Business Park, DDP Premises Number 49839 001
A1-3641379065, Dubai, UAE
Mail: info@iraj.in, www.iraj.in

Publisher: **Unified Research Library and Publishing (URLP)**

© 2026, ISERD International Conference, Hong Kong

ISBN: 978-93-90150-28-1

Edn: 710

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EDITORIAL

It is my proud privilege to welcome you all to the ISERD International Conference in Hong Kong. I am happy to see the papers from all part of the world and some of the best paper published in this proceedings. This proceeding brings out the various Research papers from diverse areas of Science, Engineering, Technology and Management. This platform is intended to provide a platform for researchers, educators and professionals to present their discoveries and innovative practice and to explore future trends and applications in the field Science and Engineering. However, this conference will also provide a forum for dissemination of knowledge on both theoretical and applied research on the above said area with an ultimate aim to bridge the gap between these coherent disciplines of knowledge. Thus the forum accelerates the trend of development of technology for next generation. Our goal is to make the Conference proceedings useful and interesting to audiences involved in research in these areas, as well as to those involved in design, implementation and operation, to achieve the goal.

I once again give thanks to the IRAJ International for organizing this event in Hong Kong. I am sure the contributions by the authors shall add value to the research community. I also thank all the International Advisory members and Reviewers for making this event a Successful one.

Editor-In-Chief

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PHOTOCATALYTIC CONCRETE BASED ON NANO-TITANIUM DIOXIDE INCORPORATING RECYCLED GLASS

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Abstract - The increasing importance given to sustainable construction materials has also accelerated interest in utilizing recycled waste and functional nanomaterials in concrete systems. Nano-titanium dioxide (TiO2), commonly preferred to impart self-cleaning functionality, is typically introduced into cementitious systems either through direct mixing or by impregnating it into aggregates In particular, the use of recycled glass as aggregate in nano-TiO2 based photocatalytic concrete is a promising approach for developing environmentally friendly and multifunctional concrete. This study investigates the effect of recycled glass aggregate, doped to nano-TiO2 based photocatalytic concrete, on photocatalytic efficiency and its environmental benefits. nano-TiO2 a potent photocatalyst, is known to decompose pollutants such as nitrogen oxides (NOx) and organic pollutants under ultraviolet irradiation. In addition, recycled glass aggregate has increased photocatalytic efficiency by allowing nano-TiO2 to benefit more from ultraviolet radiation. The combined use of recycled glass and nano-TiO2 offers a synergistic effect, contributing to both sustainability and functionality. However, challenges such as long-term durability, optimization of material proportions, and the lack of standardized testing methods remain critical issues. This study investigated the effects of using glass aggregate and nano-TiO2 on the photocatalytic and mechanical properties of cementitious systems. Overall, this study highlights the potential of recycled glass-incorporated nano-TiO2 photocatalytic concrete as a sustainable solution for modern urban infrastructure, while also identifying key research gaps for future investigations.

Keywords - Nano-TiO_2, Photocatalytic concrete, Recycled glass aggregate, Sustainability.

I. INTRODUCTION

Although concrete is one of the most widely used building materials in the world due to its high strength, long service life, and economic advantages, its production process has significant environmental impacts. In particular, cement production, a key component of concrete, is considered a major source of global environmental problems due to its high energy consumption, intensive use of natural resources, and high levels of carbon dioxide (CO2) emissions. During the clinkerization process in Portland cement production, significant amounts of CO2 are released as a result of both fossil fuel consumption and the calcination of limestone [1]-[3]. Furthermore, the cement production process is defined as an energy-intensive industrial activity due to its high temperature requirements, and it causes significant amounts of particulate matter and industrial emissions [4], [5].

With increasing urbanization and infrastructure needs, the continuous rise in concrete consumption further increases the need for sustainable and functional concrete technologies to reduce environmental impact. In this context, the use of recycled materials in concrete production stands out as an important approach in terms of both reducing the consumption of natural resources and improving waste management [6], [7]. It is stated that glass waste, due to its high silica content, can exhibit pozzolanic behavior at suitable particle sizes and can positively contribute to the microstructure of cement-based composites [8], [9]. Furthermore, various studies have shown that using recycled glass aggregates in concrete production reduces the consumption of natural aggregates, repurposes waste glass, and consequently lowers the environmental impact of concrete production [10], [11].

In recent years, the use of recycled glass aggregates in combination with photocatalytic materials has become a significant research area for the development of next-generation concretes with environmental functionality. In this context, titanium dioxide (TiO2) stands out as the most widely used semiconductor photocatalyst due to its high photocatalytic activity, chemical stability, non-toxicity, and economic availability [12]-[14]. Specifically, TiO2 in the anatase phase contributes to the decomposition of pollutants such as NOx, SOx, and VOCs in the atmosphere by promoting the formation of reactive species with high oxidation capacity, such as hydroxyl radicals and superoxide ions, under UV light [15]. Therefore, the development of photocatalytic concrete based on nano-TiO2 incorporating recycled glass constitutes an important research area for sustainable building technologies in terms of reducing natural resource consumption, recycling waste glass, and contributing to the improvement of urban air quality.

II. PHOTOCATALYTIC MECHANISM OF NANO-TIO2

TiO2 is a semiconductor photocatalyst. When irradiated with light possessing energy equal to or

greater than its band gap, electrons are excited from the valence band to the conduction band, generating electron-hole pairs [12], [16]. These charge carriers react with oxygen and water on the surface, producing reactive oxygen species such as hydroxyl radicals and superoxide ions [17] (Figure 1). The generated species can oxidize NOx, VOCs, and organic contaminants into less harmful products [18]. The anatase phase of TiO2 is generally considered more photocatalytically active than rutile because of its favorable electronic structure and slower recombination of charge carriers [19], [20]. Nano-TiO2 particles further increase the available surface area for reactions, which is why nano-TiO2 has become the dominant choice in photocatalytic construction materials [21].

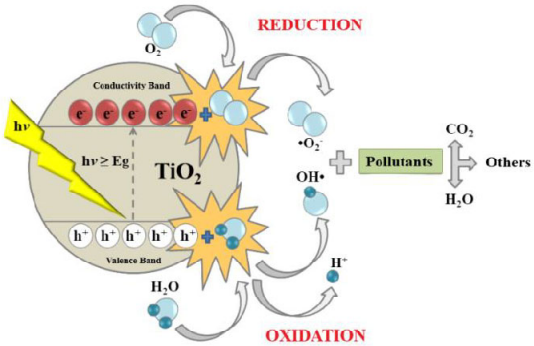


Figure 1. Oxidation-reduction reactions of TiO2

III. RECYCLED GLASS IN CONCRETE

Recycled glass can be incorporated into concrete as fine aggregate, coarse aggregate, or finely ground glass powder. The physical and chemical characteristics of glass, particularly its high silica content, make it a suitable candidate for partial replacement of conventional aggregates. Several studies have reported that appropriate amounts of recycled glass can improve certain properties of concrete, including workability and durability, while contributing to the conservation of natural resources [6], [9].

The performance of recycled glass concrete is strongly influenced by particle size, replacement ratio, and mixture composition. Fine glass particles have been shown to exhibit pozzolanic activity, consuming calcium hydroxide and contributing to the formation of additional calcium silicate hydrate (C-S-H) gel. This reaction can improve the microstructure of the cementitious matrix and enhance long-term mechanical properties [9]. Furthermore, the use of recycled glass has been associated with reductions in landfill disposal and greenhouse gas emissions related to aggregate extraction and transportation, thereby supporting circular economy principles within the construction sector [22].
Despite these advantages, the incorporation of glass aggregates may introduce challenges associated with alkali-silica reaction (ASR). ASR occurs when reactive silica present in glass reacts with alkalis in the cement pore solution, producing expansive gels that can cause cracking and deterioration. Previous research has demonstrated that ASR-related risks can be significantly mitigated through the use of finely ground glass, supplementary cementitious materials such as fly ash and slag, or optimized mixture designs [9], [23].

The use of transparent glass aggregates allows light to penetrate deep into the concrete, activating TiO2 particles beneath the surface. This can increase NOx removal efficiency by up to three times and significantly improve self-cleaning performance [24]. Transparent recycled glass aggregates have been found to be much more effective in self-cleaning and air purification efficiency compared to brown glass aggregates or mortars containing only sand. Some studies in the literature suggest that brown waste glass has no significant effect on self-cleaning efficiency [25]. Photocatalytic concretes containing glass aggregates retain their white color and aesthetic appearance much longer than traditional materials. This reduces the need for maintenance and ensures the preservation of high reflectivity, which helps reduce the urban heat island [26].

In recent years, recycled glass has gained further interest as a functional carrier material for photocatalytic coatings. Its smooth surface morphology, chemical stability, and optical properties provide favorable conditions for coating of nano-TiO2 particles. Consequently, the use of glass aggregate in photocatalytic concrete is a sustainable solution that maximizes cleaning performance by increasing light transmittance, reduces environmental pollution, and extends aesthetic lifespan. Also, TiO2-coated recycled glass aggregates have emerged as a promising approach for developing multifunctional photocatalytic concrete capable of combining environmental remediation with sustainable waste utilization.

IV. NANO-TIO_2 COATED RECYCLED GLASS FOR PHOTOCATALYTIC CONCRETE

The use of recycled glass as a support material for TiO2 nanoparticles offers several potential advantages. First, coating the aggregate surface allows a larger fraction of the photocatalyst to remain exposed to light and atmospheric pollutants. In conventional bulk incorporation methods, a significant proportion of TiO2 particles may become embedded within the cement matrix and therefore remain inaccessible for photocatalytic reactions [21], [28].

Beyond photocatalytic activity, the incorporation of TiO2-coated recycled glass aggregates may contribute to the development of environmentally responsive

concrete surfaces capable of degrading atmospheric pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), and volatile organic compounds (VOCs). Under ultraviolet irradiation, reactive oxygen species generated on the TiO2 surface can oxidize these pollutants into less harmful compounds, thereby improving urban air quality while maintaining the structural functionality of concrete [14], [29].

Despite these promising characteristics, research concerning TiO2-coated recycled glass aggregates remains relatively limited. Most existing studies have focused either on photocatalytic concrete incorporating TiO2 or on the utilization of recycled glass in concrete as separate research topics. Consequently, there is still insufficient understanding regarding the long-term durability of TiO2 coatings, coating adhesion under service conditions, abrasion resistance, photocatalytic stability, and large-scale implementation. Further experimental investigations are therefore required to optimize coating procedures, evaluate long-term performance, and establish the practical feasibility of this innovative material system [21], [30], [31].

Overall, TiO2-coated recycled glass aggregates represent a promising multifunctional component for next-generation photocatalytic concrete. By combining the pollutant-removal capability of nano-TiO2 with the sustainability benefits of recycled glass, this approach offers significant potential for supporting circular economy principles and improving the environmental performance of urban infrastructure [21], [22], [30], [32].

V. CONCLUSION

The findings summarized in this study demonstrate that the integration of nano-TiO_2 and recycled glass aggregates is a promising strategy for developing multifunctional concretes due to both its environmental and sustainability characteristics. Nano-TiO_2 provides photocatalytic functionality through the degradation of atmospheric pollutants such as NO_x and VOCs, while recycled glass simultaneously contributes to waste utilization, conservation of natural aggregate resources, and reduction of the environmental footprint of concrete production. The combination of these two materials extends the role of concrete beyond its traditional structural function, towards becoming an environmentally conscious construction material.

The literature also shows that recycled glass should be considered not only as an alternative aggregate but also as an effective substrate material for photocatalytic nanoparticles. Compared to the conventional bulk incorporation of TiO_2 into cemented matrices, TiO_2-coated glass aggregates are found to have more photocatalytically active sites and are exposed to greater amounts of ultraviolet radiation and atmospheric pollutants. Furthermore, the optical properties of transparent glass aggregates improve light transmission and scattering within the concrete matrix, potentially increasing photocatalytic efficiency while reducing the amount of TiO_2 required. Such synergistic interactions highlight the potential of TiO_2-coated recycled glass aggregates as an advanced material design that can simultaneously improve environmental functionality, resource efficiency, and long-term sustainability.

Despite all these advantages, the current literature also highlights several scientific and technological challenges that currently limit practical application. Most current studies have independently evaluated photocatalytic concrete and recycled glass concrete, but research focusing specifically on TiO_2-coated recycled glass aggregates is relatively limited. Consequently, key aspects such as coating adhesion, abrasion and weathering resistance, long-term photocatalytic stability, alkali-silica reaction compatibility, and the impact of coating properties on both photocatalytic and mechanical performance are not yet comprehensively understood. Furthermore, differences in experimental procedures and photocatalytic evaluation methods among published studies make direct comparison of reported performances difficult and underscore the need for standardized test protocols.

Therefore, future research should move beyond laboratory-scale photocatalytic efficiency measurements and focus on developing robust, economically viable, and scalable material systems suitable for practical infrastructure applications. Particular emphasis should be placed on optimizing coating techniques, controlling coating thickness and morphology, improving the interfacial bond between TiO_2 and glass substrates, and developing visible light-active photocatalysts capable of maintaining high activity under natural solar radiation. In parallel, the material development process should be accompanied by comprehensive life cycle assessments, robustness evaluations under realistic environmental conditions, and technical-economic analyses to determine the overall sustainability and commercial viability of these systems.

Overall, TiO_2-coated recycled glass aggregates represent one of the most promising approaches for next-generation photocatalytic concrete. By combining air pollutant degradation, waste glass recycling, reduction of natural resource consumption, and material functionality within a single cementitious system, this technology is closely aligned with circular economy and sustainable construction principles. Continuous advancements in photocatalysis technology, surface modification, and long-term field validations are expected to accelerate the transition of

photocatalytic concrete from laboratory research to practical application, supporting the development of cleaner, healthier, and more resilient urban environments.

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HYDRATION PERFORMANCE OF BLAST FURNACE SLAG CEMENT SYSTEMS CONTAINING MODIFIED GRINDING AIDS

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Abstract - Grinding aids (GAs) used during clinker grinding improve grinding efficiency, optimize particle size distribution, and contribute to more sustainable cement production. Beyond their role in grinding, GAs can enhance cement hydration and enable higher substitution levels of supplementary cementitious materials (SCMs), supporting lower-carbon cement and concrete systems. Although extensive research has addressed their effects on grinding efficiency, fresh properties, hydration, and rheology, their influence on blast furnace slag (BFS)-containing systems remains insufficiently understood despite BFS's high replacement potential. This study investigates triisopropanolamine (TIPA), a widely used amine-based grinding aid, modified with organic acids and polycarboxylate ether (PCE)-based water-reducing admixtures. Cements were produced using these GAs at a dosage of 0.05% by weight of clinker and gypsum. Four Portland cements, including a control without GA, were used to prepare mixtures containing 0% and 45% BFS replacement levels. Hydration behavior was evaluated using isothermal calorimetry, focusing on the maximum heat flow, the main hydration peak time, and the cumulative heat release at 24 hours. Results showed that, in BFS-containing mixtures, TIPA increased maximum heat flow by 6.42% compared to the BFS control. When modified with organic acids, this increase reached 16.51%, indicating a pronounced acceleration of early hydration. In contrast, PCE-modified TIPA reduced maximum heat flow by 8.26%, suggesting a retarding or dispersion-dominant effect. Overall, organic acid modification of TIPA significantly enhances early hydration activity in BFS-blended systems, highlighting its potential to support higher BFS substitution in sustainable cementitious materials.

Keywords - Blast furnace slag; Grinding aids; grinding aid modification; heat of hydration.

I. INTRODUCTION

The cement industry is at the center of sustainability discussions in the field of building materials due to its high production volume, energy-intensive clinkerization process, and process-related CO_2 emissions released during the calcination of limestone. Therefore, current research focuses on reducing the clinker factor, increasing grinding efficiency, lowering energy consumption, and more effectively utilizing mineral admixtures [1,2]. In particular, clinker substitution in Portland cement-based systems is considered one of the low-carbon binder strategies with high applicability in the short and medium term. This approach contributes not only to reducing environmental impacts but also to controlling the hydration kinetics, the development of the microstructure, and the long-term performance of cementitious systems.

Blast furnace slag (BFS) is one of the most important complementary binder materials used in cementitious systems. The glassy structure and latent hydraulic character of BFS enable the formation of additional C–S–H and C–A–S–H-type hydrates when activated in a suitable alkaline environment. These hydrate products can contribute to the refinement of the pore structure, the reduction of permeability, and especially the improvement of late-age strength and durability properties [3]. However, the dilution effect of BFS substitution on early-age hydration kinetics, the delay in portlandite formation, and the activation requirement of the slag reaction can limit early-age heat development and strength gain. This situation increases the importance of chemical strategies that support hydration activity in the applicability of high BFS substitution rates.

Cement hydration is a complex reaction system governed by interconnected processes, including dissolution of clinker phases, ion transport, nucleation, and growth of hydrate products [4]. Therefore, isothermal calorimetry stands out as an important method in evaluating early-age hydration behavior. Parameters such as maximum heat flow, main hydration peak time, and cumulative heat release can provide direct information about the time-dependent development of C_3S, C_3A, and C_4AF reactions and the activation level of mineral admixtures. In systems containing BFS, calorimetric analyses are particularly critical for understanding not only cement hydration but also the extent of slag activation in an alkaline environment.

Grinding aids (GAs) are traditionally used during clinker grinding to reduce interparticle agglomeration, limit electrostatic interactions, increase grinding efficiency, and achieve target fineness with lower energy consumption [5-7]. However, the effects of grinding aids extend beyond physical grinding performance. These admixtures can also influence cement particle size distribution, surface properties, dissolution behavior of clinker phases, and the rate of

hydration product formation. Therefore, grinding aids are considered in modern cement technology not only as additives that increase production efficiency but also as functional chemical components that can regulate early-age reaction kinetics and binder system performance.

Among alkanolamine-based grinding aids, triisopropanolamine (TIPA) stands out, particularly due to its effects on hydration reactions and strength development. Gartner and Myers [8] demonstrated that TIPA can enhance strength development under certain conditions by affecting the hydration of Portland cement. Subsequent studies have shown that TIPA is particularly effective on ferrite phase (C_4AF) and aluminate reactions, consequently altering the type and formation rate of hydration products [9-11]. This effect is even more significant for systems containing BFS; because TIPA's acceleration of clinker phase hydration can indirectly increase slag activation by promoting the development of portlandite and alkalinity in the environment.

In recent years, chemical modification of grinding aids has emerged as a novel research approach to achieve more targeted performance than classical alkanolamine- or glycol-based admixtures. Modifications with organic acids can alter the functional groups of the admixture, its interactions with ions, its surface adsorption behavior, and its reactivity during hydration [12]. Similarly, modifications with polycarboxylate ether (PCE)-based components can have positive effects on the dispersion and fresh-state behavior of cement particles, but due to the carboxylate groups and side-chain architecture in the PCE structure, they can also cause retarding effects on hydration kinetics or reduce the main hydration peak [13,14]. Therefore, it should not be expected that different chemical modifications of TIPA will show the same effect in systems containing BFS; the comparative effects of organic acid and PCE modifications on the heat of hydration should be investigated separately.

Although numerous studies exist in the literature regarding the effects of grinding aids on grinding efficiency, particle size distribution, fresh state properties, and Portland cement hydration, the effect of modified grinding aids on early-age hydration kinetics in BFS-substituted systems has not been sufficiently clarified [5, 8-11]. In particular, the differential effects of organic acid- and PCE-based modifications of TIPA on maximum heat flow, main hydration peak time, and 24-hour cumulative heat release at high BFS substitution rates have been studied only to a limited extent. This research aims to address this gap by calorimetrically evaluating the hydration performance of TIPA and modified TIPA-based grinding aids in Portland cement and BFS-substituted binder systems. Thus, the aim is to contribute to identifying suitable grinding-aid modifications that can increase early-age hydration activity in low-clinker binder systems containing BFS.

II. MATERIALS & METHODS

Materials

This study investigated the early-age hydration performance of Portland cement-based binder systems containing grinding aids and blast furnace slag substitute mixtures. Clinker, gypsum, blast furnace slag, and grinding aids with different chemical structures were used in the experimental study. The clinker and gypsum used in cement production were selected to be suitable for Portland cement, and material variability was minimized by using the same raw material source across all experimental series. The characteristic properties of the materials used are given in the authors' previous studies [12,15].

Blast furnace slag, used as a complementary binder material, replaced cement at a rate of 45% by mass. Thus, both plain Portland cement-based systems and low-clinker binder systems with a high slag content were evaluated comparatively. Slag-free mixtures were considered as the reference system, while slag-substituted mixtures were prepared to determine the effect of grinding aids on the hydration behavior in systems containing blast furnace slag. The grinding aids used in the study were designed to form four different cement systems. The first of these is a control cement without any grinding aid. The other cements are systems containing triisopropanolamine (TIPA), TIPA modified with organic acids, and TIPA modified with a polycarboxylate ether-based water-reducing admixture, respectively. TIPA was chosen because it is an amine-based grinding aid widely used in the cement industry. Organic acid and PCE modifications were evaluated to modify the effect of TIPA on hydration kinetics and to improve early-age reaction activity, especially in systems containing blast-furnace slag.

Preparation of Grinding Aids

The modified grinding aids used in the experimental study were obtained by modifying TIPA with different chemical components. In this context, an organic acid-modified TIPA system was prepared by reacting the TIPA-based admixture with organic acid components. In the other modification group, TIPA was evaluated together with a polycarboxylate ether-based water-reducing admixture. Thus, the effect of modifying an alkanolamine-based grinding aid with

chemical components containing different functional groups on the hydration behavior of cement and slag binder systems was investigated. Grinding aids were used at 0.05% of the total mass of clinker and gypsum during cement production. Keeping the additive dosage constant across all cements containing grinding aids enabled direct comparison of the effects of different chemical modifications on hydration performance. The control cement was prepared under the same production conditions without the addition of any grinding aid.

Cement Production and Experimental Groups

Four different Portland cements were produced as part of the study, one of which served as the control. The cement groups were classified according to the type of grinding aid used. The control cement did not contain any chemical grinding aid. The other three cements were prepared using TIPA, organic acid-modified TIPA, and PCE-modified TIPA, respectively.
The prepared cements were used to form two different binder systems with varying blast furnace slag substitution. In the first group, only cement-based mixtures were prepared without slag substitution. In the second group, 45% of the cement mass was replaced with blast furnace slag. Thus, both slag-free and slag-substituted systems were prepared for each type of cement, yielding a total of eight binder compositions.

Method

In this study, paste mixtures were prepared for hydration heat flow measurements. A high-speed special mixer was used to prepare the paste mixtures. Paste mixtures with a water/binder ratio of 0.35 were prepared. The effect of high-speed mixing on cement hydration heat flow curves was investigated using a UTCM-0347-type cement calorimeter, as specified in TS EN 196-8.

III. RESULTS T & DISCUSSIONS

The values obtained from the heat flow curves during hydration of BFS-containing paste mixtures are presented in Table 1, while the relative values compared to the control mixture (c) without GA are shown in Figure 1.

Mixtures	Max.heat flow (mW/g)	Time of the main peak during the acceleration phase (min.)	24-hour cumulative heat (J/g)
C	0.140	323	71.20
K-BFS-45	0.109	394	53.77
TIPA-0.05	0.146	263	70.70
TIPA-0.05-BFS-45	0.116	325	55.12
M-TIPA-2 -0.05	0.161	281	73.55
M-TIPA-0.05-BFS-45	0.127	346	57.71
P-TIPA-0.05	0.129	293	72.51
P-TIPA-0.05-BFS-45	0.100	360	56.76

Table 1. Maximum heat flow and cumulative heat release values at different time intervals, derived from the heat flow curves of cement pastes containing 45% BFS replacement

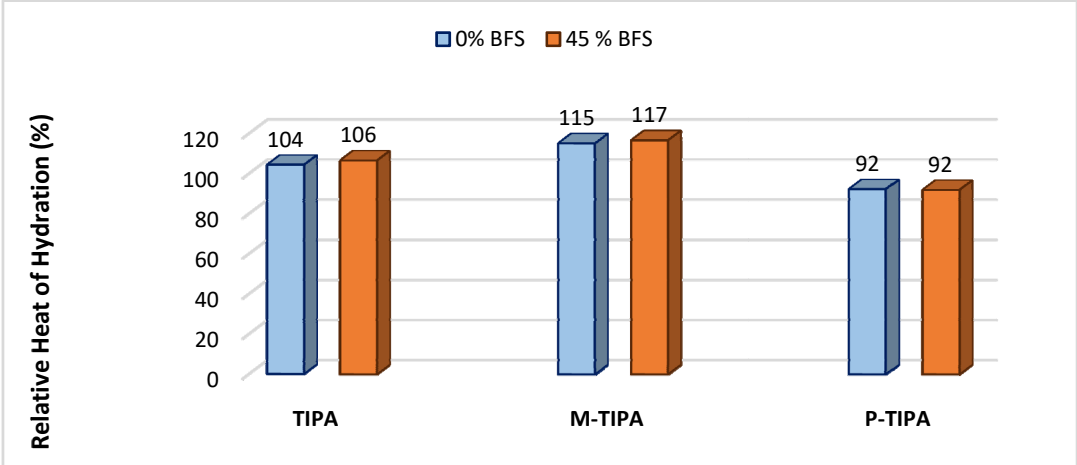


Figure 1.Relative maximum hydration heat values of GA mixtures compared to the control mixture

When 45% BFS was used as a cement replacement, the hydration heat values decreased by approximately 40%,independent of the cement type. This behavior is primarily attributed to the lower intrinsic reactivity of blast furnace slag compared to Portland cement [16,17]. In addition, BFS substitution was observed to extend the overall hydration period, with the effect being particularly pronounced during the early hydration stage.

The literature indicates that although BFS adversely affects early-age cement hydration, it may contribute beneficially to long-term strength development [18]. Overall, the incorporation of BFS reduces early-stage heat evolution in cement systems while promoting a more gradual and sustained heat release over extended hydration periods.

As presented in Table 1 and Figure 1, both the heat of hydration and the 24-hour cumulative heat release increase when TIPA is used compared to the control mixture without GA. This enhancement is even more pronounced for organic acid-modified TIPA. In contrast, PCE-modified systems exhibit lower values than the control mixture.

Previous investigations by the authors have shown that M-TIPA modified with organic acids improves adsorption characteristics and grinding efficiency, narrows the particle-size distribution of the resulting cements, and accelerates the hydration process [19,20]. Within this framework, the observed increase in hydration heat in the modified system is attributed to the additive's enhanced performance, which promotes more effective particle dispersion and reactivity during early hydration stages.

The reduction in hydration heat observed in PCE-modified systems can be attributed to PCE's influence on pore-solution chemistry, which retards the progression of hydration reactions [21].

IV. CONCLUSION

In this study, the influence of modifying TIPA, a widely used grinding aid, with polycarboxylate ether (PCE) and organic acids on the heat of hydration in BFS-substituted systems was investigated. The main findings are summarized as follows.

The heat of hydration of mixtures prepared with and without BFS replacement in the presence of TIPA was higher than that of the control mixture without GA.

In mixtures incorporating TIPA modified with organic acids, the heat of hydration was further increased compared to both the TIPA-only and control mixtures. In contrast, PCE modification reduced the heat of hydration relative to the control mixtures.

Overall, the results indicate that mixtures prepared with cements containing M-TIPA—obtained through organic acid modification—exhibit enhanced hydration heat and may enable higher levels of BFS replacement. This highlights the potential of such modifications to support more sustainable cement production processes, from clinker grinding to the development of high-volume pozzolanic cementitious systems.

ACKNOWLEDGEMENTS

The authors acknowledge that financial support for this study was provided by the Bursa Uludağ University Scientific Research Projects Unit (BAP) under Grant Nos. FBG-2025-2550, FGA-2025-2048 and FGA-2024-1754. The fourth author also gratefully acknowledges support from the Turkish Academy of Sciences (TÜBA).

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EFFECT OF UV-MODIFIED POLYAMIDE FIBERS ON MORTAR WORKABILITY AND SUPERPLASTICIZER DEMAND

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Abstract - Surface modification in fiber-reinforced cementitious composites is a widely utilized pretreatment method to enhance the fiber-matrix bonding strength. Ultraviolet (UV) irradiation stands out as a physical surface modification technique that is easy to apply and does not produce chemical waste; however, the effects of this process on fresh mortar rheology and superplasticizer requirements are not sufficiently addressed in the literature. This study aims to experimentally demonstrate how the required dose of polycarboxylate ether (PCE) changes in standard mortar mixtures containing polyamide fibers subjected to different UV exposure times (0, 5, 10, and 15 minutes). The fiber volume fraction was fixed at 0.4%, and the PCE dosage was incrementally increased until the target flow range of 185±20 mm was achieved. The results indicate that the addition of fibers increased the PCE requirement by approximately 89% compared to the fiber-free reference mixture (from 0.38% to 0.72%), and this increase became more pronounced as the UV exposure time extended. A fifteen-minute UV treatment further increased the PCE demand by 19.4% compared to the un-treated fiber group, raising it to a level of 0.86%. Although UV surface modification has the potential to enhance the interaction of polyamide fibers with the cement matrix, it increases the superplasticizer requirement in fresh mortars. Therefore, in mortar mixtures containing UV-modified polyamide fibers, the PCE dosage must be re-optimized depending on the UV exposure time to ensure the target workability.

Keywords - Fiber-reinforced mortars, Polycarboxylate ether (PCE), Polyamide fibers, Rheology, Ultraviolet (UV) surface modification.

I. INTRODUCTION

Fiber-reinforced cementitious materials constitute a category of structural materials that are increasingly widespread in contemporary civil engineering, primarily utilized to overcome the inherent brittleness of traditional cement matrices and to provide robust crack control [1]. In this context, synthetic fibers are extensively evaluated as alternative or complementary reinforcement materials to conventional polypropylene and glass fibers due to their low density, chemical stability, and diverse mechanical property ranges. Polyamide (PA, nylon-6) fibers are particularly preferred for these applications owing to their appropriate elastic modulus, processable cross-sectional dimensions, and cost-effectiveness [4].

The fundamental technical challenge in implementing fiber-reinforced mortars lies in the adverse effects fibers impose on fresh-state rheology [2]. The formation of an internal network structure restricts the free movement of the matrix components, creating additional frictional resistance within the cement paste. Furthermore, high specific surface areas and irregular fiber distribution significantly compromise flowability, increasing the yield stress of the fresh composite [3]. This consequently necessitates the use of higher superplasticizer dosages to reach target flow values [5]. It has also been demonstrated that the naturally hydrophobic, yet highly hygroscopic, surface characteristics of polyamide fibers directly influence the adsorption dynamics of water and polymer admixture ions within the cementitious paste [4], [7].

In recent years, interest in physical pretreatment methods to modify polymer fiber surfaces has surged. Ultraviolet (UV) radiation is considered a prominent methodology due to its ease of application, low operational cost, and the absence of chemical waste generation [6]. UV-C irradiation (254 nm) induces the photo-scission of amide bonds within the polymer structure, promoting surface oxidation and the formation of reactive functional groups. This process substantially increases both the wettability and the surface energy of the fibers [4], [6]. Nevertheless, the implications of these UV-induced morphological and chemical changes regarding the fresh-state behavior of mortar mixtures, particularly concerning PCE superplasticizer demand, have not been adequately investigated.

Polycarboxylate ether (PCE)-based superplasticizers are complex polymeric compounds featuring a backbone-side chain architecture. They facilitate dispersion primarily by creating electrostatic repulsion and steric hindrance following adsorption onto hydrating cement particles [8], [9], [10]. The efficiency and total adsorption capacity of PCEs depend heavily on the competitive interactions among all available surfaces within the colloidal system [10]. Therefore, as the surface roughness and chemical reactivity of the integrated fibers increase, the

competitive adsorption of PCE ions onto the fiber surfaces inevitably rises. This localized depletion decreases the free PCE concentration available for cement dispersion, thereby escalating the total dosage required to achieve the desired fluidity [11].

To bridge this specific knowledge gap, this study systematically investigates the effects of polyamide fibers subjected to varying UV exposure times (0, 5, 10, and 15 minutes) on the flow properties and PCE requirements of a standard mortar mixture. It is anticipated that the findings will supply critical, practical data for the mix design and optimization of fiber-reinforced mortars utilizing UV surface modification.

II. MATERIALS AND METHODS

A. Materials Used

1) Portland Cement

Type I Portland cement complying with the TS EN 197-1 standard [12] was used as the primary binder material. The oxide composition analysis of the cement is presented in Table I.

Oxide	Amount (%)
SiO_2	18.3
Al_2O_3	4.27
Fe_2O_3	3.23
CaO	64.68
MgO	1.65
$Na_2O + K_2O$	0.93
SO_3	3.02

TABLE I. Chemical Composition Analysis of Portland Cement

2) Polyamide (Nylon-6) Fibers

Commercially produced industrial Nylon-6 type polyamide fibers were utilized [4]. The primary physical and mechanical properties of these fibers are detailed in Table II.

Property	Value
Length	12-15 mm
Diameter	50-100 um
Density	1.13-1.15 g/cm^3
Melting point	220-230 C
Elastic modulus	3.5-5.5 GPa
Tensile strength	60-90 MPa

TABLE II. Properties of Polyamide Fibers

3) UV Radiation Source and Processing Conditions

Fiber surface modification was executed in a custom UV treatment cabinet equipped with 16 UV-C source lamps ($\lambda = 254$ nm), delivering a total power of 470 W [4]. The fibers were positioned 25 cm below the lamps to ensure homogeneous irradiation from the top and sides. Ambient conditions were strictly maintained at 20±2 °C and 50±5% relative humidity throughout the procedure. Four distinct UV exposure groups were established: 0 (control/untreated), 5, 10, and 15 minutes.

4) Standard Aggregate and PCE Admixture

River sand with a particle size range of 0-4 mm, compliant with the ASTM C33/C33M standard [13] for fine aggregates, served as the aggregate. A high-range water-reducing, polycarboxylate ether (PCE)-based superplasticizer was selected to control workability (Table III).

Admixture	Density (g/cm3)	Solid Content (%)	pH	Chlorine (%)	Alkali, Na2O (%)
PCE-based HRWR	1.060	32	2-5	<0.1	<10

TABLE III. Properties of the Water-Reducing Admixture

B. Experimental Methods

1) Mortar Mixture Proportions and Mixing Procedure

The reference and fiber-reinforced mixtures were proportioned and prepared in accordance with the ASTM C109/C109M standard [14]. To mitigate the volumetric expansion induced by fiber incorporation and preserve matrix stability, the absolute volume method outlined in the ACI 544.3R guideline [15] was implemented. Accordingly, the exact volume of 4.20 grams of polyamide fibers was calculated, and an

equivalent volume of standard river sand was deducted from the system to perform aggregate substitution. The final mixture proportions are provided in Table IV.

Mixture	Cement (g)	Water (g)	Sand (g)	Fiber (g)	Fiber Ratio	W/b Ratio
Control	500.00	242.50	1375.00	0.00	0.0%	0.485
0-5-10-15UV	500.00	242.50	1365.25	4.20	0.4%	0.485

TABLE IV. Mortar Mixture Proportions

Fresh mortars were produced using a planetary-type mixer, strictly adhering to the mechanical mixing procedure specified in ASTM C305 [16]. To prevent fiber balling and ensure homogeneous dispersion, the fibers were introduced into the matrix simultaneously with the fine aggregate.

2) Flow Test and PCE Dosage Determination Method

To accurately evaluate the UV-induced alterations in surface roughness and admixture adsorption, the 'admixture requirement determination at constant flow' method was adopted. Flow values were measured using a standard flow table apparatus in compliance with ASTM C1437 [17]. The target flow diameter was set within the narrow band of 185±20 mm for all experimental series. To achieve this consistency, the mixing water ratio was held constant while the PCE superplasticizer dosage was incrementally adjusted until the target was met.



Figure 1. Flow table test

III. RESULTS AND DISCUSSION

A. Effect of Fiber Addition on PCE Requirement

Comparative analysis against the unreinforced reference mortar revealed that introducing 0.4% polyamide fibers drastically increased the required PCE dosage from 0.38% to 0.72%, constituting an approximate 89% surge (Table V). This profound increase is fundamentally attributed to the fibers obstructing mixture fluidity by introducing extensive frictional resistance, mechanical interlocking within the fresh matrix, and a higher capacity for water and admixture adsorption. These findings corroborate behaviors observed in polypropylene fiber-reinforced systems, where apparent viscosity and yield stress escalate proportionally with fiber dosage, altering the overall PCE efficiency [11].

B. Effect of UV Exposure Time on PCE Demand

The experimental data clearly demonstrates a progressive escalation in PCE demand corresponding to extended UV treatment durations. As detailed in Table V, the 15-minute UV group (15UV) exhibited a 19.4% higher PCE requirement compared to the untreated 0UV group. The step-wise increases were recorded as follows: 0UV to 5UV (+8.3%), 5UV to 10UV (+2.6%), and 10UV to 15UV (+7.5%). The marginal rate of increase observed between the 5- and 10-minute intervals suggests that the dynamic adsorption capacity on the modified fiber surfaces may be approaching a temporary saturation threshold, or it reflects a temporary deceleration in morphological surface alterations following moderate UV dosage.

Group	PCE Dosage (g)	PCE Dosage (%)	Measured Flow (mm)
Reference	1.9	0.38	185
0UV	3.6	0.72	182
5UV	3.9	0.78	178
10UV	4.0	0.80	184
15UV	4.3	0.86	179

TABLE V. PCE Dosage Per UV Treatment Group and Measured Flow Values

C. Mechanistic Interpretation of UV Surface Treatment on Fresh-State Behavior

The photo-oxidative degradation initiated by UV-C radiation on polyamide fibers causes the targeted scission of amide bonds, generation of carbonyl and hydroxyl functional groups, and substantial micro-roughening of the surface topography [4], [6]. This physicochemical transformation forces the naturally hydrophobic fiber surface into a highly hydrophilic state while dramatically expanding its specific surface area. Consequently, when dispersed within the fresh mortar, these UV-modified fibers

sequester a significantly larger volume of free mixing water and active PCE polymer chains.

Previous optimization studies support the premise that higher superplasticizer dosages are mandatory to fluidize matrices containing UV-treated fibers [4]. From a rheological standpoint, the fraction of PCE chains adsorbed onto the expansive fiber surfaces is effectively sequestered from the broader cement paste dispersion mechanism; thus, it cannot contribute to the deflocculation of cement particles [10]. To compensate for this localized polymer depletion and reach the target fluidity, the total PCE dosage must be proportionally increased. This phenomenon mirrors the classic steric hindrance principles governing PCE interactions with cement grains [8], [10], but crucially extends the competitive adsorption interface to include the high-surface-energy polymer fibers.

Furthermore, the augmented topographical roughness inherently intensifies inter-particle frictional resistance and mechanical interlocking. This aligns seamlessly with the current literature highlighting the dualistic nature of fiber surface modifications: while such pretreatments are vital for enhancing interfacial transition zone (ITZ) bonding, they inevitably inflict a rheological penalty [1]. Consequently, the optimization of UV exposure time must carefully balance the acquired structural benefits of enhanced fiber-matrix adhesion against the fresh-state workability costs associated with elevated superplasticizer demands.

IV. CONCLUSIONS

This study experimentally investigated the effects of UV-C modified polyamide fibers on the fresh-state rheology and PCE-based superplasticizer requirements of standard mortar mixtures. The primary findings are summarized as follows:

The incorporation of untreated polyamide fibers at a 0.4% volume fraction significantly impaired workability, driving the necessary PCE dosage from 0.38% (reference mortar) up to 0.72%, representing an 89% increase.

Extending the UV processing duration progressively exacerbated the PCE demand. The required superplasticizer dosages reached 0.78%, 0.80%, and 0.86% following 5, 10, and 15 minutes of UV application, respectively. The 15-minute exposure induced a severe 19.4% additional PCE requirement relative to the untreated fiber mixture.

While UV surface modification holds significant potential to fortify the mechanical interaction between polyamide fibers and the cementitious matrix, it generates a substantial, competitive admixture requirement. Therefore, standard PCE dosages must be rigorously re-optimized in direct correlation with the selected UV exposure time.

The rheological costs of UV processing must be evaluated holistically alongside its structural benefits. Future comprehensive investigations should correlate these macroscopic workability changes with microstructural and chemical verifications utilizing FTIR, SEM, and contact angle goniometry.

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PUBLIC AWARENESS OF FLOOD RISK IN MONTENEGRO: CHALLENGES AND OPPORTUNITIES FOR IMPROVED RESILIENCE

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Abstract - Floods are among the most common natural hazards, posing significant risks to communities worldwide, including Montenegro. This study assesses public awareness of flood risks in Montenegro, aiming to identify preparedness levels and highlight areas for improvement. This paper underscores the importance of public awareness in reducing flood vulnerability and improving community resilience. The survey was conducted to assess public awareness and get insights into respondents' awareness of flood preparedness measures. Also, the study's objective was to identify preferred actions for improving resilience to floods. The results offer recommendations for politicians and highlight the need for new strategies, including public education. By addressing these challenges, Montenegro can strengthen its capacity to manage flood risks effectively and build a more resilient society.

Keywords - flood hazard,flood risk, flood risk assessment, public awareness

I. INTRODUCTION

Floods are among the most common natural hazards worldwide, affecting urban and rural communities. Climate change is increasing the likelihood of severe flooding, and many regions face unprecedented challenges in flood risk management [1,2]. Montenegro's diverse topography of mountains, rivers, and coastal areas is particularly vulnerable to floods. Effective flood risk management requires infrastructure, policy, and a well-informed public which understands the risks and is prepared to respond to flood events. To point out the importance of public awareness in flood risk reduction, this research aims to determine the level of preparedness for flood events.

Publicawareness meansunderstanding flood risks, knowledgeof personal and community-level protection, and a willingness to adopt proactive measures. Much research has investigated public knowledge and communities' preparedness for flood events [3,4,5]. Research highlights that informed communities are more likely to take preventive actions and make quick decisions during crises, ultimately reducing vulnerability and enhancing overall resilience[6,7]. Without widespread awareness, communities may be unable to respond effectively, thereby increasing vulnerability. Montenegro's current public awareness levels regarding flood risks are not well-documented, making it challenging for policymakers to develop targeted education and preparedness programs.This study aims to assess the current public awareness of flood risk in Montenegro. The paper investigates how individuals understand flood risks and their level of preparedness.By identifying these factors, the study highlights Montenegro's challenges in fostering a flood-resilient population and suggests potential improvement opportunities.

II. FLOOD RISK IN MONTENEGRO

2.1. Overview of flood risk assessment in Montenegro

The Preliminary Flood Risk Assessment (PFRA) in Montenegro represents the first step in implementing the EU Flood Risk Management Directive (2007/60/EC) requirements. It was completed in December 2021. The PFRA includes historical and potential future flood events that may significantly affect human health, the environment, cultural heritage and economic activities.

In developing PFRA, available data were used to calculate the probability of return periods of 10, 100 and 500 years. The results were calibrated based on flood data from 2010, which is considered the most significant flood on record. During the assessment, expected climate change impacts were considered using one extreme flood scenario (recovery period from extreme floods ≥ 500 years), which included future impacts, including climate change impacts. The work on scenarios of extreme flood events covers the effects of climate change on identifying areas with significant flood risks.Regarding future floods, it can be concluded that flood events will be more frequent and intense due to climate change [8,9]. Therefore, although total annual precipitation is expected to decrease in most of the watershed in Montenegro[10], in the future, short-term heavy rainfall, often combined with snowmelt and soil saturation, is expected to cause a greater risk of flash floods caused by increased surface insularity.

Based on the analysis of all the data mentioned

above, 19 Areas of Potential Significant Flood Risk (APSFR) in the water area of the Adriatic and Danube basins were defined and presented in GIS format. Hazard maps and flood risk maps were developed for the 19 APSFR areas. A description of damage, potential risks/assets in the flood area together with the importance of possible risks to human health, environment, economic and cultural criteria are presented for high (return period 10 years), medium (return period 100 years) and high risk (return period 500 years) flood events, for each APSFR.

The risk assessment for each APSFR, based on significance criteria and threshold values, identified potentially significant issues related to human health, economic values, environmental risks, and cultural heritage sites.
A program measure was created that includes flood prevention, flood protection and preparedness, which includes:

- measures aimed at measuring/avoiding an increase in flood risk (e.g. in connection with planning);
- flood protection measures using natural flood management;
- measures that protect against floods using traditional engineering methods;
- flood preparation measures in case they occur (e.g., flood warnings, awareness raising, and emergency intervention plans).

2. 2. The platform for flood risk assessment - national and municipal level

The Institute for Hydrometeorology and Seismology in Montenegro is primarily responsible for flood warnings. When extreme meteorological conditions indicate a potential flood, the Institute alertsthe Ministry of Internal Affairs' Emergency Situations Administration, which notifies all relevant local and national authorities, including municipal protection and rescue services. The Institute operates a network of measuring stations along rivers to monitor water levels, regularly gathering data on river flow to provide timely information essential for early warnings and risk assessment.

Montenegro’s disaster risk management (DRM) framework outlines targeted protective measures across all phases—prevention, preparedness, response, and recovery—emphasizing the safety of residential areas, infrastructure, and cultural assets. Although DRM plans often include general statements about spatial planning and other protective measures, there are instances where risk analysis directly informs preventive actions, especially in identifying areas prone to landslides or rockfalls. However, in the response phase, these plans are less consistently linked to risk analysis findings, potentially due to data limitations that may affect the accuracy of consequence assessments.

Flood risk analysis in Montenegro's flood rescue and protection plans is generally based on case studies of past floods, which highlight vulnerabilities and inform resource prioritization. These analyses are conducted on a municipal level, and no criteria exist for defining critical infrastructure.

By studying the extent and impact of historical floods, authorities can pinpoint vulnerable areas, inform evacuation planning, and improve early warning systems, enhancing the overall preparedness of local authorities. Although specific infrastructure is not considered critical, data on exposed infrastructure in flood-prone areas helps develop evacuation procedures and swift response efforts.

The relevant documents for flood risk assessment at the municipal level for emergency management in Montenegro are:

- Disaster Risk Management Capability Assessment,European Commission—Directorate-General for European Civil Protection and Humanitarian Aid Operations (DG ECHO), spanning 2022-2024, coordinated by the Ministry of Interior's Rescue and Protection Directorate (RPD) in Montenegro (DRMCA, 2023)[11]: This assessment thoroughly examines administrative, technical, and financial capacities concerning various risks, notably flood risk.
- Law on Protection and Rescue[12]: This legislation serves as a comprehensive regulatory framework governing protection and rescue efforts at both national and local levels. It mandates risk assessment, management planning, and appropriate measures.
- Rulebook on the Methodology for Developing Protection and Rescue Plans[13]: This rulebook outlines the methodology for creating and updating plans addressing protection and rescue from diverse disasters and accidents. It delineates the responsibilities of state bodies, local government units, companies, and other entities in developing municipal protection and rescue plans.
- Municipal plans for protection and rescue: Compliant with the Rulebook, these plans comprise information on potential flood risk, protective measures, operational units, human and material resources, readiness implementation, mobilization methods, management responsibilities, intervention actions, safety protocols, risk mitigation strategies, financial resource allocation, public information dissemination, acceptance and provision of assistance from other municipalities

or states, and necessary topographic maps and documents.

III. SURVEY DESIGN

The survey was conducted to evaluate public awareness of flood risks in Montenegro, gather insights into respondents' familiarity with flood preparedness measures, and identify preferred actions for improving resilience to floods. A descriptive-type study was prepared, utilizing multiple-choice questions with predefined answers to ensure clarity and uniformity in responses. The survey was designed to be concise and accessible, consisting of seven questions, allowing participants to complete it in less than one minute.

3.1. Survey implementation

The survey was created using Google Forms, which enabled seamless data collection and ensured participant anonymity. The survey was distributed nationwide across all 25 municipalities of Montenegro through the personal contacts of the researchers, including outreach via email, messaging applications, and direct invitations. By leveraging existing networks, the researchers ensured broad participation and diverse representation of respondents from urban and rural areas alike.

The survey was conducted over a 12-day period, from November 8th to November 19th, 2024. A total of 622 completed questionnaires were collected. While 13 municipalities reported fewer than 10 responses, all collected data were considered valid and representative to conclude nationally. The emphasis of this study was not on municipality-specific analysis but rather on identifying overall trends and key findings for the entire country.

3.2. Survey structure

The survey questions can be grouped into three main categories, to focus on crucial areas related to public awareness and preparedness for flood risks. The questions systematically capture critical insights on the current level of flood awareness among respondents, their preparedness and knowledge of protective measures, and their openness to enhancing flood resilience through education or policy interventions. The mentioned categories through which the survey can be analyzed are the following:

1. Socio-demographic section (2 questions): the age of the surveyed occupants and the municipality where they reside.
2. Flood risk awareness and preparedness section (3 questions): familiarity with flood risks (to assess how aware individuals are of flood hazards in their communities); training and information dissemination (to determine whether respondents have received education or preparedness training); and evacuation route awareness (to evaluate knowledge about designated evacuation routes and shelters).
3. Willingness and priorities for improvement section (2 questions): willingness to dedicate time to flood preparedness education (to explore respondents' readiness to engage in educational activities related to floods); and priority measures for improving preparedness (to identify community preferences regarding measures to enhance flood resilience).

3.3. Respondent participation

The survey targeted the general population without restrictions on demographic or regional criteria. The sample size of 622 respondents was deemed sufficient to provide meaningful insights. The highest percentage of survey respondents are in Podgorica (54.0%), followed by Nikšić (12.9%) and Pljevlja (4.8%), while several municipalities, such as Plav, and Tuzi, had the lowest representation at 0.2%. This distribution follows the number of inhabitants in those municipalities. The age group distribution is shown in Table 1.

Age group	Number of Respondents (out of 622)	Percentage of respondents (%)
Under 19 years	44	7.1
20 to 39 years	304	48.9
40 to 59 years	234	37.6
60 years and older	40	6.4

Table 1: Share of survey respondents belonging to different age group

IV. SURVEY RESULTS AND DISCUSSION

This chapter presents the key findings from the survey and discusses their implications for improving public awareness and resilience to flood risks in Montenegro. The responses highlight significant gaps in flood preparedness and offer insights into the measures that could be prioritized to strengthen community resilience.

4.1. Familiarity with flood risks

The survey revealed varying levels of familiarity with flood risks among respondents, as shown in Figure 1. A notable 64% of respondents indicated either partial or no familiarity with flood risks in their communities. This level of unfamiliarity is particularly concerning as it suggests that a significant portion of the population may be unaware of the hazards they face, limiting their ability to prepare adequately for flood events. Such a lack of awareness can result in slower emergency responses, increased damage, and higher risks to personal safety. Addressing this issue through targeted awareness campaigns and accessible educational initiatives is

essential for improving overall flood preparedness.

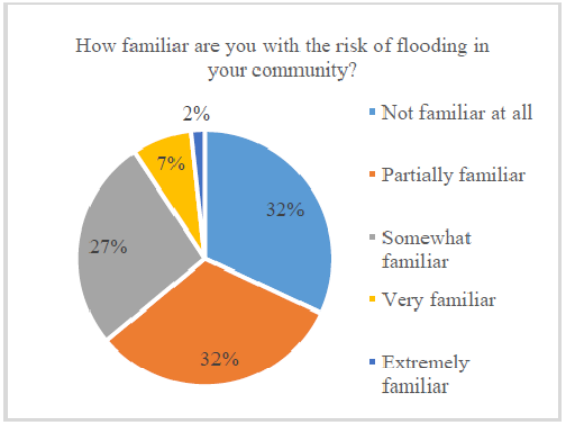


Fig. 1. Share of respondents with different familiarity with flood risks

4.2. Information and training on flood preparedness

When asked whether they had received any information or training on flood preparedness, most of respondents (477 out of 622, or 76.7%) reported not having received any information. The remaining responses were distributed as shown in Figure 2.

These findings highlight the limited role of official institutions in disseminating flood preparedness information. Local authorities and educational programs appear underutilized as channels for flood risk education. Expanding the scope of public training initiatives could significantly enhance preparedness.

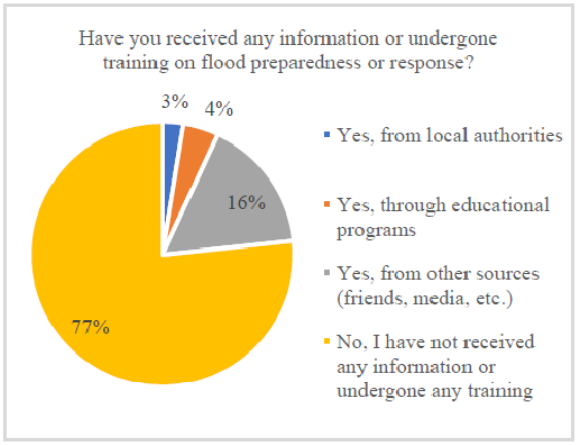


Fig. 2. Distribution of responses regarding flood preparedness information or training

4.3 Awareness of evacuation routes and shelters

Respondents were asked about their knowledge of designated evacuation routes and shelters in their area. The majority (514 respondents, or 82.6%) reported not being informed, while only a small fraction demonstrated full awareness (Fig. 3).

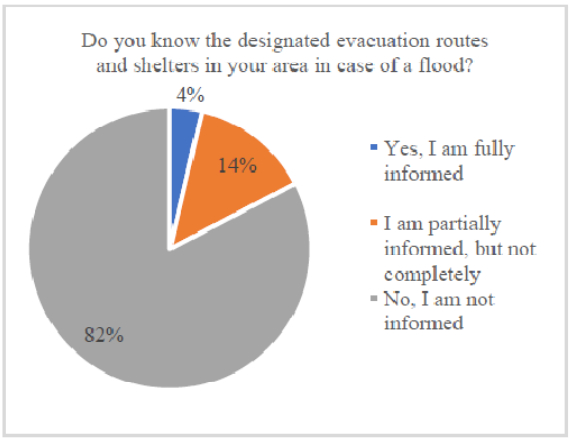


Fig. 3. Awareness of designated evacuation routes and shelters among respondents

This lack of knowledge poses a critical risk during flood emergencies, as uninformed individuals may face delays or confusion when evacuating. Public awareness campaigns and community drills are essential to improve familiarity with evacuation protocols.

4.4 Willingness to dedicate time to flood preparedness

The survey explored willingness to engage in flood preparedness education.

Respondents were asked about the amount of time they would be willing to dedicate to flood preparedness education. The results are shown in Figure 4.

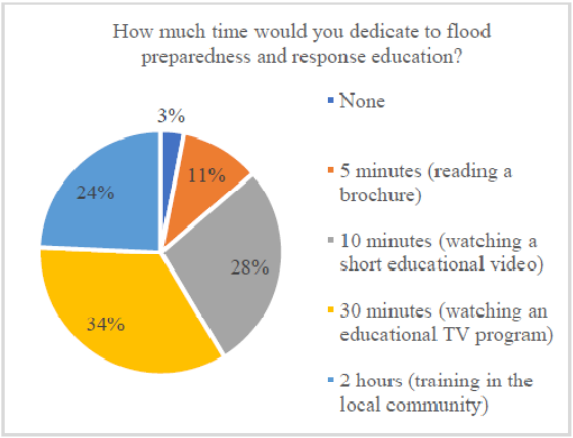


Fig. 4. Willingness of respondents to dedicate time to flood preparedness education

These findings demonstrate a positive willingness to engage in educational activities, particularly through accessible media formats such as videos and TV programs. However, a considerable portion of respondents (34%) expressed readiness to participate in community-based training, indicating strong potential for local engagement.

4.5. Priority measures for improving flood preparedness

The survey explored preferred measures for improving resilience to floods. The survey allowed respondents to select multiple measures, reflecting the importance of integrating both structural and non-structural approaches to flood resilience. Structural measures, such as flood-resistant infrastructure, are critical for mitigating physical damages, while non-structural measures, like early warning systems and community education programs, play a vital role in preparedness and response. This holistic perspective highlights the necessity of balancing physical defenses with public awareness and behavioral changes to achieve comprehensive flood risk management. The most frequently chosen measures that the respondents believed should be prioritized to enhance community awareness and preparedness are: the development of flood-resistant infrastructure (381 votes), regular notifications via media and social networks (333 votes), improved early warning systems (309 votes), emergency preparedness programs in schools (292 votes), andworkshops or community training (232 votes).

The results underscore the need for both structural and non-structural measures to improve flood resilience. While infrastructure development remains a clear priority, respondents also emphasized the importance of regular communication, education, and early warning systems. This combination of measures could effectively address existing gaps in public awareness and preparedness.

4.6. Discussion

The survey results provide critical insights into Montenegro's current flood risk awareness. The findings highlight significant deficiencies in public knowledge, training, and preparedness. One of the most vital challenges identified in this study is the general lack of public awareness of flood risks. Furthermore, the lack of awareness regarding evacuation routes presents a serious challenge for effective emergency response.

A notable opportunity emerging from this study is the potential for increasing public engagement through educational campaigns. Respondents demonstrated a strong willingness to engage in educational activities, preferring practical and accessible formats such as videos, TV programs, and community workshops. Additionally, prioritizing infrastructure development and early warning systems indicates clear areas for policy focus and investment.

Montenegro can enhance its flood preparedness and improve resilience by addressing these challenges. Key initiatives suggested by the results include enhancing flood-resistant infrastructure, implementing early warning systems, and promoting community education programs. Additionally, introducing school emergency preparedness programs and leveraging regular media communications can be critical in building public awareness and preparedness. These measures, when combined, offer a robust foundation for strengthening the country's capacity to mitigate flood risks and respond effectively to flood events. It can enhance its flood preparedness and build more resilient communities.

V. CONCLUSION

The research involved a nationwide survey of 622 respondents, focusing on awareness, training, and attitudes toward flood preparedness measures. Findings reveal significant gaps in public knowledge, with 64% of respondents unfamiliar with local flood risks and 82.6% unaware of evacuation routes and shelters. Additionally, 76.7% reported receiving no information or training on flood preparedness. Despite these deficiencies, the study identified a strong public willingness to engage in educational activities, emphasizing accessible formats like videos and community-based workshops. Respondents also prioritized flood-resistant infrastructure and early warning systems as essential measures for improving resilience. Integrating structural and non-structural approaches, such as enhanced infrastructure, public education, and early warning systems, is critical to mitigating flood risks.

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Appendix A

Below is translated version of the survey questionnaire; the original was in Montenegrin.

Respected,
As part of the project "Flood Risk Assessment in Montenegro: Depth-Damage Relationships for Areas of Potential Significant Flood Risk" (FLORIAS), funded by the Ministry of Science and Technological Development of the Government of Montenegro, we are surveying as part of the research. The project represents a comprehensive initiative to improve flood risk assessment and more effective flood risk management in Montenegro. The project is led by the Faculty of Civil Engineering at the University of Montenegro, and the partner on the project is the Directorate for Water Management of Montenegro.

The survey is anonymous. It consists of 7 questions that take less than a minute to complete. Your answers will significantly improve the research results and create more effective measures for managing flood risks.
Thank you in advance for your time!

For more information about the project, you can visit: www.florias.me

- What age group do you belong to?

- under 19 years
- from 20 to 39 years
- from 40 to 59 years
- 60 years and more

- How familiar are you with the risk of flooding in your community?

- Not familiar at all
- Partially familiar
- Somewhat familiar
- Very familiar
- Extremely familiar

- Have you received any information or undergone training on flood preparedness or response?

- Yes, from local authorities
- Yes, through educational programs
- Yes, from other sources (friends, media, etc.)
- No, I have not received any information or undergone any training

- Do you know the designated evacuation routes and shelters in your area in case of a flood?

- Yes, I am fully informed
- I am partially informed, but not completely
- No, I am not informed

- How much time would you dedicate to flood preparedness and response education?

- None
- 5 minutes (reading a brochure)
- 10 minutes (watching a short educational video)
- 30 minutes (watching an educational TV program)
- 2 hours (training in the local community)

- In your opinion, which measures should be prioritized to improve community awareness and preparedness for flood risks? (Multiple answers can be selected)

- Workshops and training in the community
- Improved early warning and notification systems
- Regular notifications through media and social networks
- Development of flood-resistant infrastructure
- Introduction of emergency preparedness programs in schools

★★★

COMPARISON BETWEEN SINGLE AND MULTI-STAGE TRIAXIAL COMPRESSIVE STRENGTHS OF SOME ROCK TYPES

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Abstract - This study aims at correlating the triaxial compressive strengths obtained from multi-stage testing with those from the conventional single stage test condition. Results from ten rock types are used to determine Hoek-Brown parameters under confining pressures ranging from 0 to 40 MPa. The ratio of Hoek-Brown parameters obtained from multi-stage testing to that of single stage testing (i.e. m_m/m_s) can correlate well with the rock uniaxial compressive strengths (with $R^2 > 0.9$) using an exponential equation. As a result, the triaxial compressive strength of rock can be closely predicted providing that the Hoek-Brown parameters from multi-stage testing and the uniaxial compressive strengths of the rock are known. The correlation of the strength results between the two test conditions however strongly depends on the loading path used during the multi-stage testing. Different loading paths would likely result in a different $m_m/m_s - \sigma_c$ relation.

Keywords - Hoek-Brown Criterion, Strength Criteria, Multi-Stage Triaxial Testing,

I. INTRODUCTION

The triaxial compression test (ASTM D7012-14) [1] has been widely used to determine rock strength and deformation under confinement, which are important parameters for the design and stability study of geological structures in civil as well as mining engineering works, including foundations for dams, structures, and bridges, and additional host rocks for underground mining and tunnels. The triaxial compression test is used in the laboratory to simulate these structures. A significant limitation of the traditional triaxial test method is that it is expensive, time-consuming, and requires a large number of standard samples. The multi-stage triaxial compression test ([2], [3] and [4]) is more popular nowadays because it requires fewer samples to determine the triaxial strength. It is found that the multi-stage strength is often lower than the singlestage strength. The differences and representativeness of the multi-stage test results and the deformation modulus however require more investigation.

The multi-stage triaxial test concept was first introduced in the mid-1970s [5]. It is necessary to test a variety of rocks to conduct a comparative study of the singlestage and multi-stage strengths. Accurate lateral and axial stresses of the specimen are typically difficult to measure due to non-uniform deformations of the specimen and local strain measurement by measuring equipment [6].

The objective of this study is to develop mathematical correlations between single stage and multi-stage triaxial compressive test results in terms of strength and deformability. Hoek-Brown strength criterion and Goodman stiffness relation between intact and fractured rocks are employed. Ten rock types with strength varying from soft to strong rocks are used. A polyaxial load frame is used to load and unload the specimens, which allows determining the compressive strengths and deformation moduli of the rocks under both single and multi-stage testing.

II. SAMPLE PREPARATION

Rock specimens come from various locations in Thailand. Rock specimens are prepared from ten different rock types, ranging from soft to hard rocks, including TakFa gypsum, MahaSarakham salt, KhaoKhad bedded limestone, PhuKradung sandstone, KhaoKhad marble, PhaWihan sandstone, PhuPhan bedded sandstone, PhuPhan sandstone, Rayoung-Bang Lamung granite, and Buriram basalt. Prismatic specimens are prepared with nominal dimensions of 54 × 54 × 108 mm³. The bedding planes for sedimentary rocks are oriented perpendicular to the primary axis

III. TEST METHOD

There are two types of triaxial tests: single stage triaxial compression tests and multi-stage triaxial compression tests. The objective of the triaxial compression tests is to determine the parameters (m and s) of the specimens in accordance with the Hoek-Brown criterion [7] under varying confining pressures. After the confining pressure is increased a desired magnitude, the axial stress increases at rate of 1 MPa/s until failure occurs while the confining pressure is maintained constant. To find the strength envelope, the specimens are tested at different confining pressures in a single-stage behavior under axial stress until it fails, as per the ASTM standard procedure (ASTM D7012-14) [1]. The multi-stage triaxial compression testing aims to measure the maximum failure stress and axial and lateral strains

during loading and reloading phases by conducting a multi-stage loading using polyaxial compression frame [8]. These tests are carried out under constant confining pressures between 0 and 40 MPa. The multi-stage stress path is shown in Fig 1. Under hydrostatic conditions, confining pressure (σ_3) and axial (σ_1) stress are first simultaneously increased to the required confining pressure. The axial stress is then raised to failure and then released to the original confining pressure. Both axial and confining stresses then increased to the next level of confining pressure. After that, axial stress is once raised to reach the peak strength. This cycle is repeated to allow analysis of rock strength at various confining pressures. Axial stress and strains and lateral strains are plotted continuously from the first to the last loading stages.

IV. TEST RESULTS

The results of single stage triaxial compression tests conducted under confining pressures (σ_3) ranging from 0 to 40 MPa. They are performed to compare with the multi-stage triaxial tests. Extension failure is observed in high-loading specimens. The high confining pressures result in multiple fractures. Some post-tested singlestage specimens are shown in Fig 2(a).The results of multi-stage triaxial compression tests. These tests are performed to compare with the single stage triaxial tests. The specimens exhibit varying failure patterns depending on the applied stress level at each stage. Under confining pressure, deformation was observed to gradually increase as each subsequent step was initiated at a higher confining pressure.

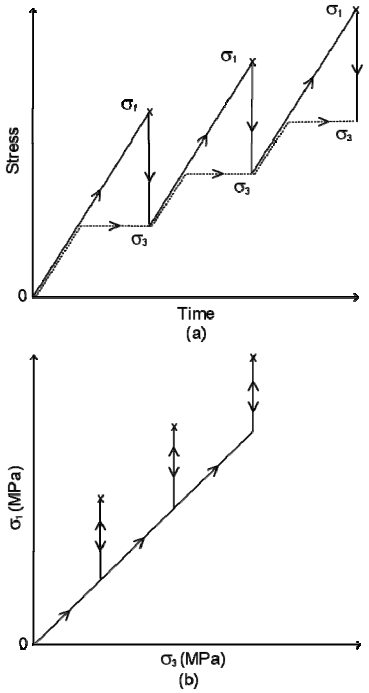


Fig.1. Stress path for multi-stage triaxial compression test used in this study, (a) variations over time and (b) confining pressure (σ_3).

Some post-tested multi-stage specimens are shown in Fig 2(b). The test results are presented as stress-strain curves in Fig3 and 4.

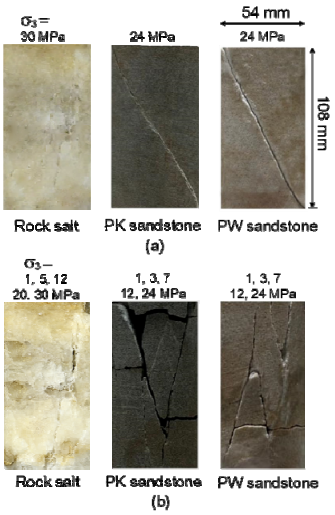


Fig.2. Some post-test specimens for single stage (a) and multi-stage triaxial compression tests (b).

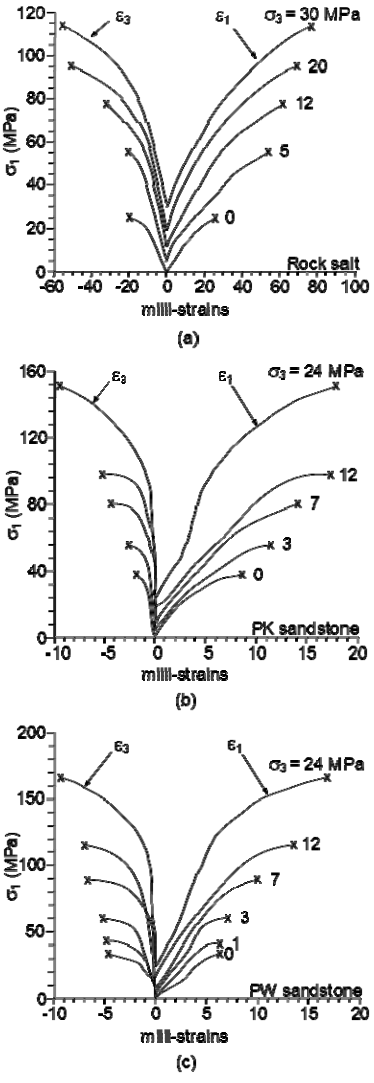


Fig.3. Some stress-strain curves obtained from Rock salt (a), PK sandstone (b), and PW sandstone (c) specimens with single stage triaxial compression tests.

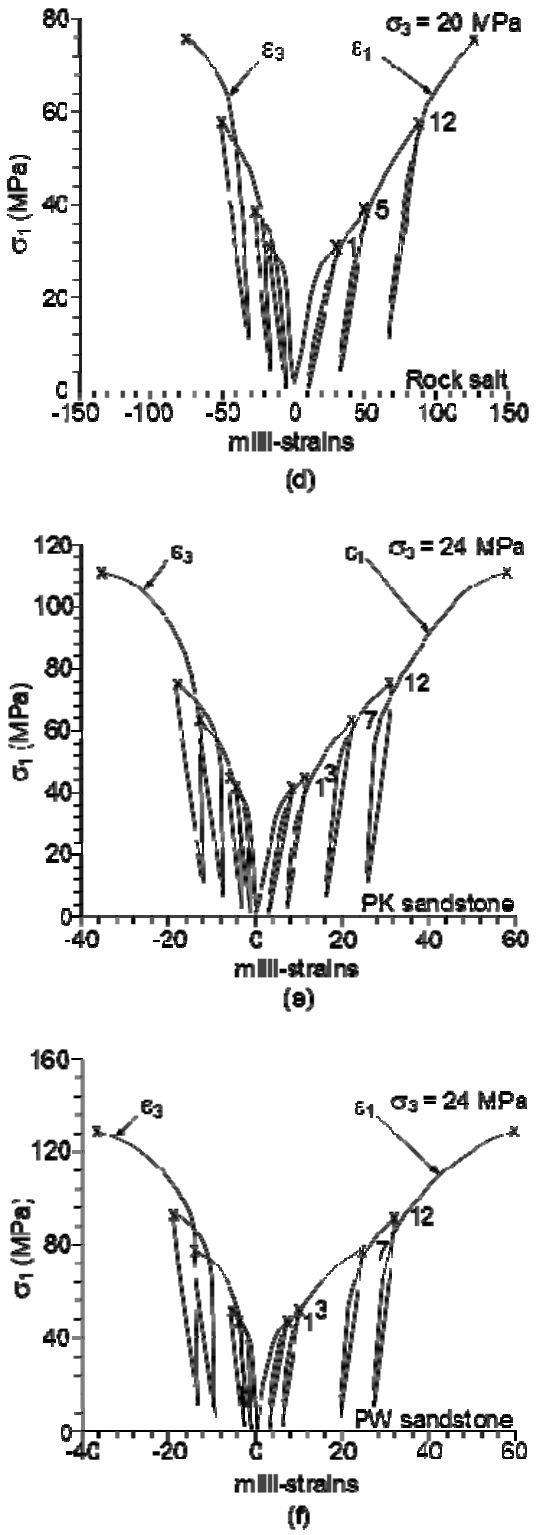


Fig.4. Some stress-strain curves obtained from Rock salt (d), PK sandstone (e), and PW sandstone (f) specimens with multi-stage triaxial compression tests.

4.1. Strength results

Hoek-Brown criterion [7] is applied to the triaxial compression strengths, using data obtained from both single and multi-stage test conditions, based on the compressive strengths of test results in Table 1. It represents the principal stresses at failure ($\sigma_{1,f}$):

$$\sigma_{1,f} = \sigma_3 + (m \cdot \sigma_c \cdot \sigma_3 + s \cdot \sigma_c^2)^{1/2} \quad (1)$$

where $\sigma_{1,f}$ is compressive strength at failure, σ_3 and σ_c are confining pressure and uniaxial compression strength of rock. The parameters m and s are empirical constants. Regression analyses are performed on the test results to determine these parameters. The $\sigma_{1,f}$–σ_3 curves obtained from the regression are compared with the test data for all rock types in Fig 5. Good correlations are obtained (R^2> 0.9).

Rock Types	Confining pressure σ_3 (MPa)	$\sigma_{1,f}$ (MPa)	
		Single stage	Multi-stage
TakFa gypsum	0	10.8	-
	1	-	11.3
	3	17.9	13.3
	7	28.3	18.1
	12	40.8	24.6
	18	51.3	33.1
MahaSarakham salt	0	25.1	-
	1	-	27.2
	5	55.3	35.9
	12	77.1	54.1
	20	95.6	71.5
	30	114.2	89.5
KhaoKhad bedded limestone	0	32.6	-
	1	-	35.2
	5	64.2	50.3
	8	78.3	61.2
	16	107.1	85.6
	30	149.1	121.5
PhuKradung sandstone	0	38.9	-
	1	-	40.4
	3	58.0	43.7
	7	77.7	62.4
	12	97.2	73.7
	24	151.3	110.7
KhaoKhad marble	0	41.7	-
	1	-	43.5
	3	65.4	50.3
	7	83.2	66.3
	12	105.2	85.3
	20	139.7	109.3
	35	186.9	147.2
PhaWihan sandstone	0	43.3	-
	1	-	46.8
	3	63.4	51.3
	7	88.9	76.6
	12	106.9	91.3
	24	166.4	129.0
PhuPhan bedded sandstone	0	53.7	-
	1	-	55.3
	3	78.3	63.5
	7	105.4	84.6
	12	130.2	108.4
	24	186.5	144.9

Rock Types	Confining pressure σ_3 (MPa)	$\sigma_{1,f}$ (MPa)	
		Single stage	Multi-stage
PhuPhansandstone	0	55.0	-
	1	-	57.2
	4	95.7	75.3
	12	138.8	110.5
	20	180.4	147.3
	36	235.9	195.3
Rayong-Bang Lamung granite	0	59.1	-
	1	-	61.0
	5	-	86.2
	10	140.3	115.4
	20	191.3	157.4
	30	225.3	191.9
Buriram basalt	0	100.6	-
	1	-	107.3
	10	192.1	175.3
	20	271.2	240.5
	30	331.9	290.3
	40	376.5	325.4

Table 1: Summary of single and multi-stage triaxial compression test results.

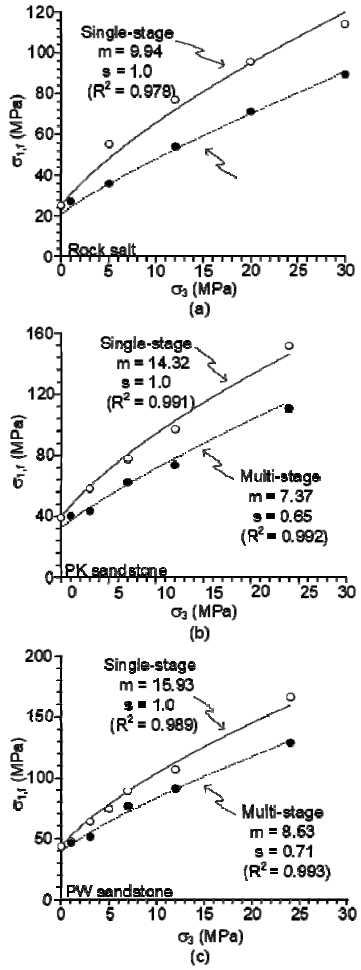


Fig.5. Compressive strengths at failure as a function of confining pressure for MahaSarakham salt (a), PhuKradung sandstone (b), PhaWihan sandstone (c).

An attempt is made to correlate Hoek-Brown parameters obtained from the two test conditions. Since both parameters depend on uniaxial compression strength of rocks. They are plotted as a function of σ_c in Fig 6. The parameter m increases with σ_c. where single stage test condition gives higher values than the multi-stage condition. The parameter s for the single stage test is equal to one for all rock types as it is calibrated from the intact rocks. For multi-stage testing however parameter s shows the values of less than one. The weaker rocks give the lower s values than the stronger rocks (higher σ_c).

To correlate the Hoek-Brown parameters between the two test conditions, the subscript m denoting multi-stage is assigned for the multi-stage parameters (m_m and s_m), where subscript s (denoting single stage) is using for the single stage parameters (m_s and s_s). After several trials, ratios of the Hoek-Brown parameters are proposed as: m_m/m_s and s_m/s_s. They are plotted in Fig 7. Exponential equations are fitted to these ratios. Good correlation is obtained. They can be presented as:

$$m_m/m_s = 1 - a \cdot \exp(-b \cdot \sigma_c) \quad (2)$$

$$s_m/s_s = 1 - c \cdot \exp(-d \cdot \sigma_c) \quad (3)$$

when a, b, c, d are empirical constants. The m_m/m_s ratio allows predicting then m_s value for single stage testing of the m_m value is known for the multi-stage testing. Extrapolation of the two equations above allows predicting the uniaxial compressive strengths of rocks at which the m_m/m_s and s_m/s_s approach one are given in Table 2.

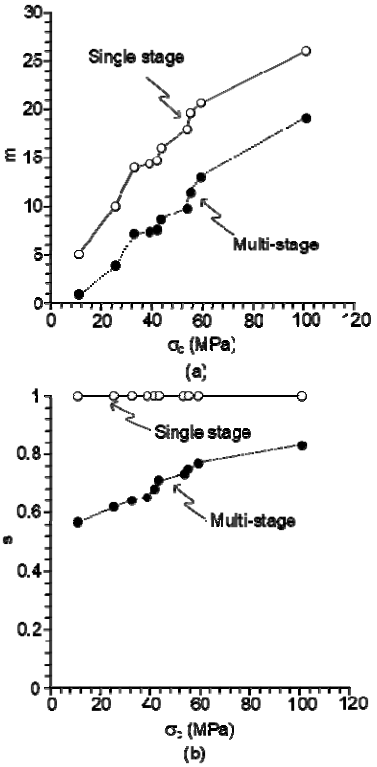


Fig.6. Hoek-Brown parameters, m (a), and s (b) as a function of uniaxial compressive strength (σ_c).

4.2. Strengths from researches obtained elsewhere

Fig 8 compares the m_m/m_s ratio obtained from this study with those published by other researches who conduct both multi-stage and single stage compression testing on various rock types. The solid points in the diagram represent the results obtained from the same loading path are used in this study. The open data points are those from different loading paths of multi-stage testing. The error between the prediction and the results obtained elsewhere are calculated using equations as follows [9]:

$$\text{Error} = 1/n \; |m_m/m_{s\,(i,\,p)} - m_m/m_{s\,(i,\,t)}/m_m/m_{s\,(i,\,p)}| \cdot 100 \quad (4)$$

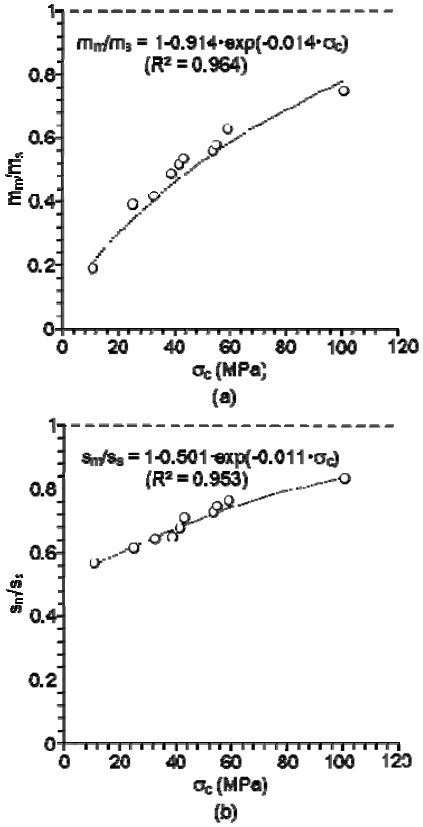


Fig.7. Relationship between m_m/m_s ratios (a), and s_s/s_m ratios (b) as a function of uniaxial compressive strength (σ_c).

Rock Types	m_m/m_s	s_m/s_s
TakFa gypsum	0.19	0.57
MahaSarakham salt	0.39	0.62
KhaoKhad bedded limestone	0.42	0.64
PhuKradung sandstone	0.43	0.65
KhaoKhad marble	0.51	0.68
PhaWihan sandstone	0.54	0.71
PhuPhan bedded sandstone	0.56	0.73
PhuPhan sandstone	0.58	0.75
Rayong-Bang Lamung granite	0.63	0.77
Buriram basalt	0.74	0.83

Table 2: m_m/m_s and s_m/s_s ratios obtained from single and multi-stage strength results.

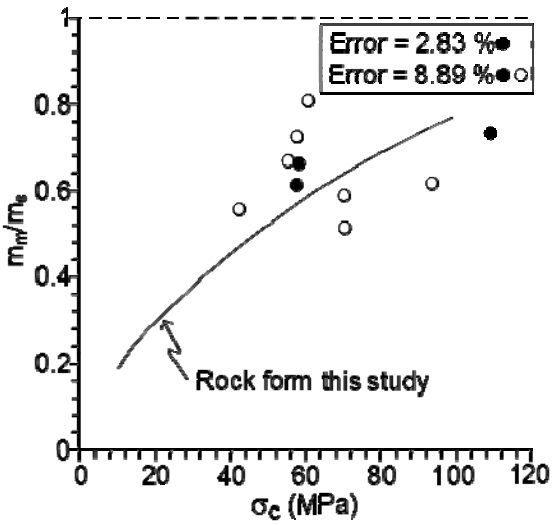


Fig.8. Solid points are results from [3]. Open points are from others: [9], [10], [11], [12].

V. DISCUSSIONS

Due to the fact that the $\sigma_{1,f}$–σ_3 relations for all tested rocks are not linear, as shown in Fig 5, the conventional Coulomb strength criterion is not applicable here. In addition, the criterion is only for intact rock specimens, and hence it is not valid for the multi-stage testing specimens where they are failed after the first loading cycle. Hoek-Brown criterion seems more appropriate for this study as it is capable of describing the compressive strengths of the intact specimens for the single stage tests and the failed specimens for multi-stage testing.

Rock types selected for this study have uniaxial compressive strengths ranging from soft rock (gypsum – 10.8 MPa) to strong rock (basalt – 100.6 MPa). This allows deriving an appropriate mathematical relations between m_m/m_s ratios and the strength (i.e., Equation (2)). Missing from this study is the very strong rock specimens (σ_c> 250 MPa), as they are rarely encountered in the geo-engineering projects and mines in Thailand.

Good correlations between m_m/m_sratio and $\sigma_c$and between s_m/s_s ratio and $\sigma_c$support that the triaxial compression strengths for the single stage testing that uses several specimens to accomplish can be predicted by the results of the multi-stage testing that uses much fewer specimens. As a minimum the multi-stage testing requires only one uniaxial compression test to obtain $\sigma_c$and one multi-stage triaxial testing to obtain m_m and s_m. The three parameters can be used to predict m_s and s_s (always equals to 1) for the single stage testing.

Comparison of the correlation equation obtained from this study with the multi-stage strength results obtained elsewhere by other researchers suggests that the multi-stage strengths are sensitive to the loading path. If a multi-stage testing uses the same loading path that used here the prediction by Equation (2) can

give good correlation with the error of about 2.83%, as shown in Fig 8. For multi-stage strengths obtained under different loading paths (i.e., not allowing axial stress to drop from the failure stress to the current confining pressure), as performed by [10], [11], and[12], larger error can be obtained, as shown in Fig 8.

VI. CONCLUSIONS

Test results and analyses performed in this study can be concluded as follows.

1. Hoek-Brown criterion can be used to correlate the triaxial compressive strengths between single and multi-stage testing.
2. Good correlation between m_m/m_s ratio and uniaxial compressive strength allows predicting the conventional single stage triaxial compressive strengths from the multi-stage compressive strength results.
3. The multi-stage triaxial strengths are sensitive to the loading paths used for each loading cycle. Different sets of compressive strengths would likely be obtained under different loading paths.

ACKNOWLEDGMENTS

This study is funded by Suranaree University of Technology and by the Higher Education Promotion and National Research University of Thailand. Permission to publish this paper is gratefully acknowledged.

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EXPLORING THE IMPACT OF CAFFEINE ON SLEEP AND COGNITIVE PERFORMANCE IN AIR TRAFFIC CONTROL: EXPERIMENTAL FINDINGS AND INSIGHTS

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Abstract –

StudyObjectives
Most current models for predicting alertness, particularly in relation to cognitive performance, mainly rely on limited factors like sleep and caffeine consumption. This study examines caffeine's effect on cognitive performance, namely response time and sleep, in the context of air traffic control. We sought to test how accurately the 2B Alert Web system can predict cognitive performance with different amounts of sleep deprivation and caffeine intake.

Methods
We report here for analysis a four-day-long experiment of the Human Factors Laboratory of the Mohammed VI International Academy of Civil Aviation, including 39 volunteers. Participants' reaction times were recorded and compared with forecasts made by the 2B Alert Web system, allowing examination of the system's ability to predict cognitive performance during sleep deprivation and in the presence of caffeine.

Results
Results indicate a clear inverse relationship between caffeine consumption and reaction time, meaning caffeine appears to enhance performance. The effects of caffeine on sleep were, however, more inconsistent. A group of particular participantsshowed no perceivable effects of caffeine on either reaction time nor sleep. Going deeper into this subgroup, it was found that 75% of these individuals reported that they did not have enoughrest, and all reported stress. This indicates that stress and rest play a conspicuous role in cognitive performance.

Conclusions
Where caffeine generally improves reaction times, the other factors that could impact cognitive performance flexibly vary from one person to the other. The study emphasizes the significance of considering stress and rest apart from caffeine while assessing cognitive performance. Such relevance is especially pivotal in domains such as air traffic control, where cognitive function is paramount to safety and efficiency. The implications are for further scientific research into what other factors, other than caffeine, can exert an influence on performance in high-pressure environments.

Significance
This study contributes to a better understanding of caffeine's role in cognitive performance in aviation and emphasizes that cognitive function needs more than
good caffeine optimization for air traffic control purposes. Stress levels and adequate rest should also be taken into account. These insights are valuable for refining predictive models and improving performance in air traffic control and other high-stress professions.

Keywords - Physio-cognitive modeling, Sleep, Caffeine, Cognitive performance, Stress, Rest, Unified Model of Performance, 2B Alert Web.

I. INTRODUCTION

Cognition involves the brain processes involved in obtaining, processing, and using knowledge. These processes affect how we see the world, remember things, make decisions, and solve problems. All of these factors affect some cognitive functions that are important for our daily lives; from simple duties to very complex, they play a vital role in individual performance and do play a part in the health of an individual. Understanding the impact of caffeine consumption, for example, on cognition can help us in forming appropriate strategies to enhance cognition and healthy living.Both sleep and coffee are very essential for effective cognitive functioning. Sleep is the very basis of our cognitive abilities and, in particular, our degree of alertness, memory, and problem-solving skills. On the other hand, caffeine is commonly used to temporarily enhance alertness and mental performance. Mathematical models have emerged as a powerful tool for predicting and improving cognitive performance by incorporating these factors into structured frameworks.

More recent developments in mathematical modeling such as the Unified Model Performance have provided valuable insights regarding the interplay between sleep, caffeine, and cognitive function. The objective of this review is to consolidate these advancements, explore the applicability of these

developments, and identify spheres of improvement. Furthermore, we underlined the importance of integrating furthervariables to make these models more calibrated and efficient.

II. THEORETICAL BACKGROUND

A. Cognitive Processes and Their Relevance

Cognition consists of multiple essential processes: Perception is defined as the process by which we interpret sensory information from our environment. Perception is critical to orienting attention and making decisions and judgments.

Memory encompasses the processes of encoding, storage, and retrieval of information.

Decision-Making: This is the process of choosing between different options, using both rational analysis and emotional responses.

Problem-Solving: This involves finding solutions to complex issues by combining memory, perception, and decision-making skills.

All these cognitive functions can be affected by sleep and caffeine; therefore, understanding their precise effects has increased in importance.

B. The Unified Model of Performance (UMP)

The Unified Model of Performance (UMP) puts different factors together, which could predict cognition performance.It combines sleep-wake regulation, the effects of caffeine, and their interactions to simulate cognitive outcomes. The main components of the UMP are the following:

Performance Function (P(t)) indicates the changes in cognitive performance over time, which reflects the aspects of how sleep and alertness impacts performance level.

Sleep-Wake Regulation (S(t)) denotes how cognitive performance is influenced in general by either sleep or circadian rhythms.

Caffeine Effect (C(t)) identifies the effect of caffeine on cognitive function, taking in consideration factors like the dosage, timing, and fading of caffeine over time. Combined Performance (P-combined(t)) shows how sleep-wake regulation and caffeine affect performance.

Theoretical models, like the UMP, are grounded in principles from cognitive science, physiology, and pharmacology. To further understand these models, it’s necessary to understand these concepts:

Circadian rhythms: Natural processes that complete a typical cycle every 24 hours, influencing our alertness and performance.

Sleep architecture: How sleep cycles are structured and how they influence cognitive functions. Caffeine pharmacokinetics: Absorption, distribution, metabolism, and elimination of caffeine from the body, including its effects on the central nervous system.

C. 2B Alert Web

O'Connor and Clark (2017, p. 552) argue that the 2B Alert Web application plays a crucial role in applying principles of the Unified Model of Performance (UMP) in real-life settings, particularly in fields such as air traffic control where high levels of awareness are imperative. With the 2B Alert Web being a supportive web application, continuous visualization of various states, such as a person's sleep history and caffeine intake, enables the, prediction of cognitive performance and alertness based on the UMP.The study assesses the accuracy and reliability of these predictions by comparing them with actual performance data such as reaction times across different sleep and caffeine consumption regimens.The ability of the 2B Alert Web to assess performance and dynamically update the prediction in real-time gives it a huge advantage in high-stress environments. The 2B Alert Web makes continual adjustments to the initial prediction based on individual input, leading to better personalized strategies to enhance cognitive performance and alertness. This can thus lessen the effects of fatigue and improve general performance.The study also elucidates the manner by which 2B Alert Web can serve to review and validate the UMP in enhancing safety and efficiency in critical sectors such as aviation.

III. METHODS

A. Literature review

An extensive review of current research on mathematical models related to sleep and caffeine was conducted. Key sources include:

- Ramakrishnan et al. (2016): This study focused on validating the Unified Model of Performance (UMP) across different sleep/wake schedules, highlighting the model's robustness and adaptability.
- McCauley et al. (2013): Their work explored how circadian rhythms impact performance models, emphasizing the need to account for these daily fluctuations in cognitive function.
- Benitez et al. (2009): This research looked at models of minimal performance inhibition, offering insights into how fatigue affects performance and its broader implications.

These studies form a foundation for understanding how performance models have evolved and how they are applied in real-world settings. Additionally, other research on caffeine, individual differences, and practical applications was also reviewed.

B. Governing Equations of the Unified Model ofPerformance

Impairment of performance: P(t)

C and S denote the circadian and homeostatic processes of the two-process model at time t, respectively, whereas κ indicates the circadian amplitude.

$$P(t) = S(t) + \kappa C(t)$$

Circadian process (C):

$$C(t) = \sum_{i=1}^{5} a_i \sin\left[i\frac{2\pi}{\tau}(t+\varphi)\right]$$

where $a_j i = 1, \ldots, 5$, are the amplitude of the five harmonics ($a_i = 0.97, a_2 = 0.22, a_5 = 0.07, a_s = 0.03$, and $a_5 = 0.001$), τrefers to the period of the circadian oscillator ($\sim 24h$), and φis the circadian phase.

Homeostatic process (S) :

$$\frac{dS(t)}{dt} = \begin{cases} [U - S(t)]/\tau_w & \text{during wakefulness} \\ [L(t) - S(t)]/\tau_s & \text{during sleep} \end{cases}$$

In this context, U and Lrefer to the upper and lower asymptotes of process S, whereasτ_w and $\tau_z$indicatethe time constants related to increasing and decreasing sleep pressure during wakefulness and sleep, respectively. $S(0) = S_0$ and $L(0) = L_0$are the initial state values for S and L, respectively.

Sleep debt (Debt):

$$\frac{dDebt\,(t)}{dt} = [Loss\,(t) - Debt\,(t)]/\tau_{LA}$$

$$Loss\,(t) = \begin{cases} 1 & \text{during wakefulness} \\ -2 & \text{during sleep} \end{cases}$$

where $\tau_{LA}$is the time constant of the exponential decay of the effect of sleep history on performance.

The UMP forecasts the impact of sleep history, time of day (t), and caffeine dosage (c) on alertness impairment (P), as measured by the mean reaction time (RT).

$$P(t, \theta) = P0(t, \theta) \times gPD(t, \theta, c) \quad (1)$$

$$P0(t, \theta) = S(t, \theta) + \kappa C(t, \theta) \quad (2)$$

P0 signifies the impairment of alertness in the absence of caffeine, S indicates the homeostatic process, K represents the amplitude of the circadian process C, gPD symbolizes the stimulating impact of caffeine, and θ encompasses 12 model parameters.

C.Sampling

This experimental study involved 39 participants who were selected to take part in a simulation for air traffic control. Over the course of four days, the participants were tasked with completing a series of tasks within the simulation.To ensure consistency and reliability, all participants had to meet specific inclusion criteria, ensuring they were familiar with the simulation environment and had a similar baseline level of cognitive function. During the study, each participant performed the same tasks, ensuring controlled conditions and consistency throughout the experiment.

Input Variables

The study assessed several key input variables:

- Caffeine Consumption: Daily caffeine intake was documented for each participant, with quantities varying from 0 to 360 mg.
- Sleep Duration: Participants provided self-reported data on their total nightly sleep hours.
- Rest and Stress Levels: Psychological factors like rest and stress were measured subjectively, with participants rating these aspects daily.

Output Variables

The main output variable in this study was reaction time, measured in two different ways:

Measured Reaction Time (PVTB): Participants' reaction times were evaluated daily using a stimulus-based test called the Psychomotor Vigilance Test (PVTB). These reaction times ranged from 200 to 320 milliseconds (ms).

Predicted Reaction Time (2B ALERT WEB): Using the 2B Alert Web application, participants' caffeine intake and sleep hours were entered into the system daily. Based on this data, the system predicted reaction times, which ranged from 191 to 320 milliseconds (ms).

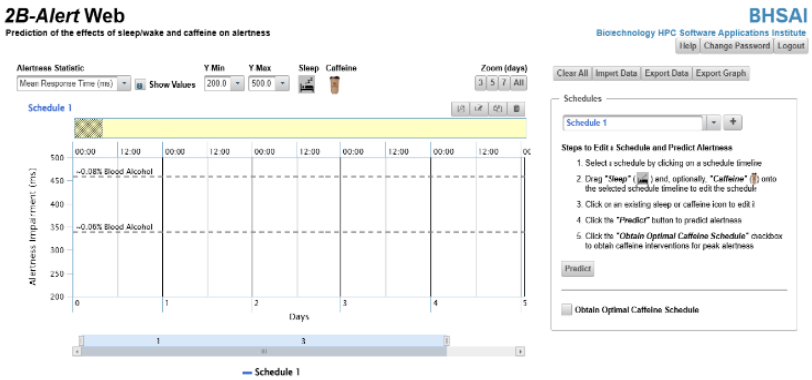


Fig. 1: 2B Alert Web application

D.Survey instrument

A questionnaire was designed to gather detailed information about participants' daily activities and overall health. It begins with demographic questions to understand participants' backgrounds, followed by sections focused on specific lifestyle factors. These include sleep habits, caffeine and food consumption, physical activity levels, and performance on the Psychomotor Vigilance Test (PVT), which measures attention and reaction speed.The survey also assesses mood, stress levels, rest, and general well-being, providing a comprehensive view of how these factors might interact and affect an individual's health and performance. By collecting data across multiple categories, the survey aims to identify potential correlations and trends that could contribute to larger health-related studies or initiatives.

E. Data Collection

Data were collected over a four-day period, during which participants completed a daily task in the air traffic control simulator. Each day, participants recorded their caffeine intake, hours of sleep, and provided subjective ratings of their mood and stress levels. Reaction times were measured using a stimulus-based test, and the input data were then entered into the 2B Alert Web application to calculate the predicted reaction times. Both the measured and predicted reaction times were documented for further analysis.

F. Prediction Calculation

Reaction times were predicted using the 2B Alert Web system. The application took the input data—specifically caffeine consumption and sleep duration—to calculate an estimated reaction time for each participant. This predicted value was then compared with the actual reaction times recorded during the stimulus test conducted in the simulation sessions.

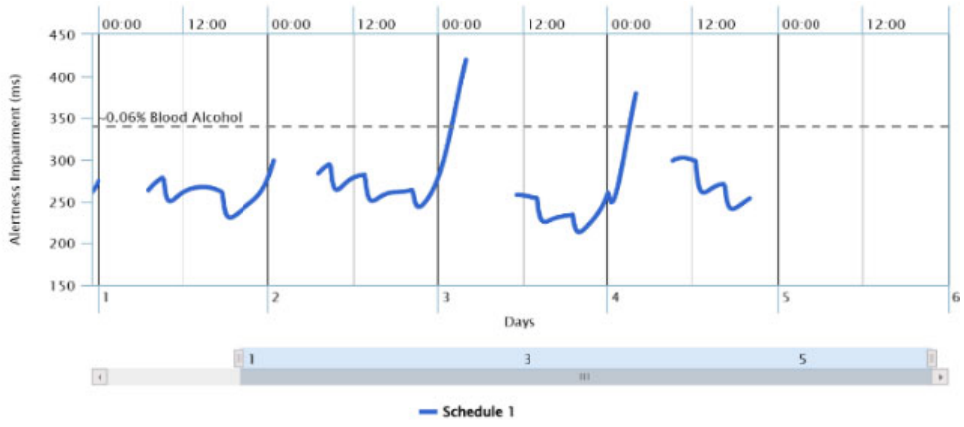


Fig. 2: Results of the 2B Alert Web of a participant's reaction time as a function of time of the day

Inputs													Outputs					
Sleep Schedule				Caffeine Schedule			Peak Alertness Schedule				Maximum Daily Caffeine (mg)	Desired Minimum Peak Alertness (ms)						
Start		End					Start		End									
Day	Time	Day	Time	Day	Time	Dose (mg)	Day	Time	Day	Time			Time	Sleep(0)/ Wake(1)	Days (x-axis)	Mean Response Time (ms)	Mean Speed (1/s)	Lapses (#)
1	00:00	1	07:00	1	09:09	90							07:00	1	0,29	251,08	4,18	3,83
2	01:00	2	07:00	1	17:24	90							07:01	1	0,29	251,27	4,18	3,84
3	04:00	3	11:00	2	08:46	90							07:02	1	0,29	251,46	4,18	3,84
4	04:00	4	09:00	2	13:37	90							07:03	1	0,29	251,64	4,18	3,85
				2	20:25	70							07:04	1	0,29	251,83	4,18	3,85
				3	14:03	90							07:05	1	0,30	252,01	4,17	3,86
				3	19:04	90							07:06	1	0,30	252,19	4,17	3,86
				4	00:05	90							07:07	1	0,30	252,37	4,17	3,87
				4	12:24	90							07:08	1	0,30	252,55	4,17	3,87
				4	16:27	90							07:09	1	0,30	252,73	4,17	3,88
				4	20:00	90							07:10	1	0,30	252,91	4,17	3,88
													07:11	1	0,30	253,08	4,16	3,89
													07:12	1	0,30	253,26	4,16	3,89
													07:13	1	0,30	253,43	4,16	3,90
													07:14	1	0,30	253,60	4,16	3,90
													07:15	1	0,30	253,78	4,16	3,91
													07:16	1	0,30	253,95	4,16	3,91
													07:17	1	0,30	254,12	4,16	3,91
													07:18	1	0,30	254,28	4,15	3,92
													07:19	1	0,30	254,45	4,15	3,92
													07:20	1	0,31	254,62	4,15	3,93

Fig. 3: Participant's sheet predicted by 2B AlertWeb

G. Comparative Evaluation

We used a variety of data visualization tools to explore how caffeine impacts response speed and sleep. To start, we used scatter plots to show the relationship between caffeine intake, both observed and predicted reaction times, and sleep duration. We then added regression lines to these plots to better understand the trends in the data, specifically looking at how coffee consumption might influence performance and sleep.

We also added mean lines to the scatter plots for sleep duration, providing a clear reference for comparison. Participants were divided into two subgroups—caffeine users and non-caffeine users—to allow for a deeper analysis of how caffeine affected each group. A Venn diagram was used to visualize the overlap between these groups, highlighting participants whose caffeine consumption didn't seem to affect either their reaction times or sleep.

Finally, a pie chart was used to show the distribution of rest and stress levels across the different subgroups, helping us see how factors beyond caffeine—like rest and stress—might influence the overall results.

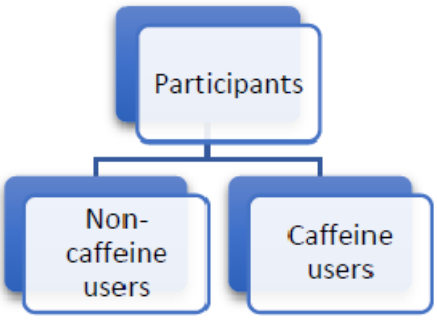
IV. RESULTS

CAFEINE	Impact on Reaction Time
	Impact on Sleep

We divided the results into two categories: one focusing on the impact of caffeine on sleep, and the other examining how caffeine affected reaction time.

A. CAFEINE IMPACT ON REACTION TIME

Some participants consumed caffeine, while others abstained. We then divided the data within each category into two groups: those who used caffeine and those who did not.



i.Caffeine users

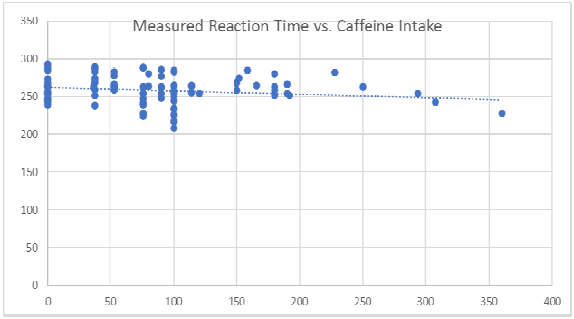


Fig.4: Scatter plot with regression of measured reaction time as a function of caffeine consumption

The scatter plot shows the recorded reaction times of participants in relation to their caffeine consumption. Each point represents an individual, with the x-axis indicating caffeine intake and the y-axis showing their reaction time. The negative regression line reveals an inverse relationship between caffeine consumption and reaction time, meaning that as caffeine intake increases, reaction times tend to decrease. This suggests that higher caffeine consumption is linked to better performance, as individuals with more caffeine typically respond more quickly.

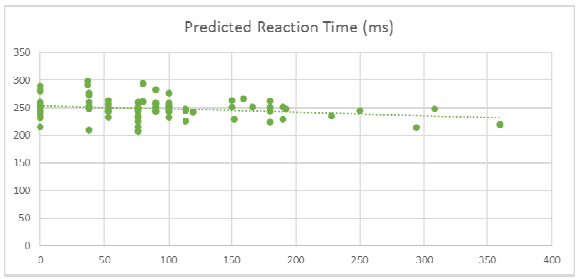


Fig.5: Scatter plot with regression of predicted reaction time as a function of caffeine consumption

The scatter plot shows the predicted reaction times from the 2B Alert Web system based on participants' caffeine intake. Each point represents a prediction linked to the amount of caffeine consumed, with caffeine shown on the x-axis and predicted reaction time on the y-axis. The negative slope of the regression line suggests that, according to the model, an increase in caffeine consumption is associated with a decrease in the predicted reaction time. This means that the 2B Alert Web system predicts faster reactions as caffeine intake rises.

The negative correlation seen in both the actual reaction times and the predicted ones—whether from the real data or the 2B Alert Web system—reveals a consistent trend: as caffeine consumption increases, reaction time decreases. This supports the idea that coffee boosts performance by improving reaction time. Both the experimental findings and the model's predictions indicate this negative relationship, reinforcing existing research and further supporting the link between caffeine use and improved cognitive function.

ii. Non-Caffeine users

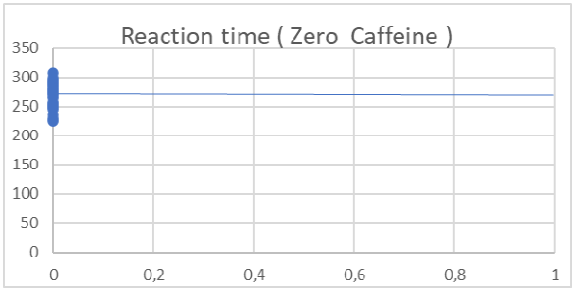


Fig 6: Scatter Diagram of Reaction Time in Non-Caffeine Users with Mean Line

The scatter plot shows the recorded reaction times for non-caffeine users, with each point representing the reaction time of an individual. The x-axis represents the participants, and the y-axis shows the recorded reaction time in milliseconds. A horizontal mean line is placed at 270.5 ms, which marks the average reaction time for this group. Most of the data points

are clustered around this mean, suggesting that reaction times for non-caffeine users are generally close to this value, though there's some variation between individuals.

iii. Caffeine users and non users

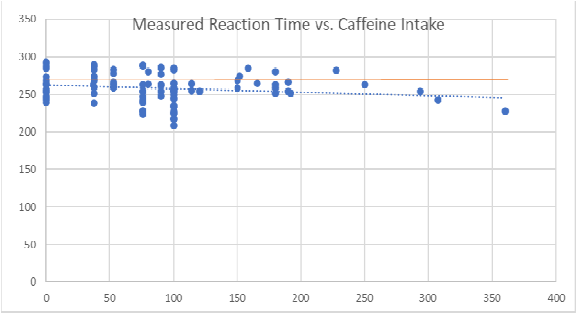


Fig.7:Scatter Diagram of Measured Reaction Times in Caffeine Users with Non-Caffeine User Mean Line

The scatter plot shows the reaction times of caffeine consumers, with each point representing an individual's reaction time. A horizontal mean line, which represents the average reaction time of non-caffeine users, is set at 270.5 ms. While most of the data points are spread out around the reaction times of caffeine users, some participants have reaction times close to the mean line of non-caffeine users, despite their caffeine consumption. This suggests that coffee may not always improve performance for everyone, indicating that other factors could be influencing their reaction times and overall performance.

The participants near the mean line 270,5 are P1, P5, P6, P7, P17,P19, P20, P22, P32, P33, P36

A. CAFEINE IMPACT ON SLEEP

i. Caffeineusers:

The scatter plot shows sleep duration in relation to caffeine consumption, with each point representing an individual participant. The negative slope of the regression line suggests an inverse relationship: as caffeine consumption increases, sleep duration tends to decrease. This points to a correlation between higher caffeine use and reduced sleep, highlighting caffeine's potential impact on sleep patterns.

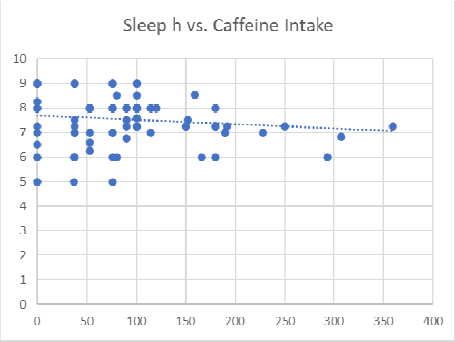


Fig.8:Scatter Diagram of Sleep Duration in Relation to Caffeine Intake

ii. Caffeine non-users:

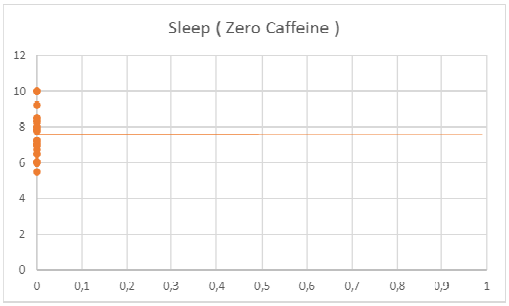


Fig 9: Scatter Diagram of Sleep Hours in Non-Caffeine Users

The scatter plot shows sleep duration in relation to caffeine consumption among non-caffeine users, with each point representing an individual's sleep duration. The x-axis represents caffeine consumption (which is zero for this group), and the y-axis shows the corresponding sleep duration in hours. A horizontal mean line is set at 7.25 hours, indicating the average sleep duration for this group. Most of the data points cluster around this mean, suggesting that non-caffeine users typically sleep for about 7.25 hours, with little variation among participants.

iii. Caffeine users and non-users

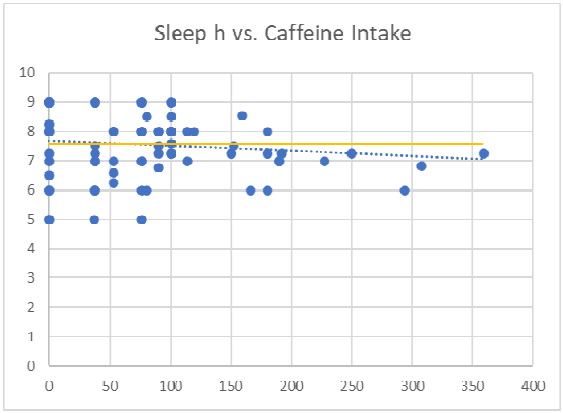


Fig.10: Sleep Duration in Caffeine Users with Mean Line for Non-Users

The scatter plot shows the sleep duration of coffee consumers, with each point representing an individual's sleep length. The x-axis indicates caffeine consumption, while the y-axis shows sleep duration in hours. A horizontal mean line at 7.25 hours represents the sleep duration of non-caffeine users. Some caffeine consumers have sleep durations close to this mean, suggesting that their sleep length doesn't differ much from that of non-caffeine users, despite their caffeine intake. This implies that coffee might not be the only factor affecting sleep, and other variables could be influencing sleep patterns as well.

These participantsnear the mean line 7,25 h are:P1, P3, P4, P7, P13, P17, P22, P24

B. Stress and Rest in Non-Responders to Caffeine

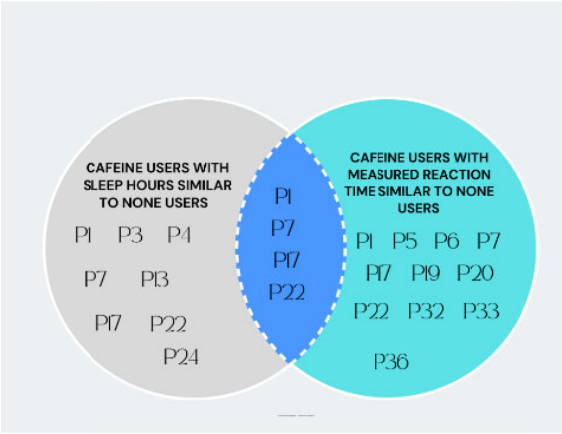


Fig 11:Venn Diagram of Participants with No Caffeine Effect on Reaction Time or Sleep

The Venn diagram shows the overlap between participants who experienced no effect of coffee on their reaction speed and those who showed no effect on their sleep. The two circles represent these groups, and the overlapping area highlights individuals who were unaffected by coffee in both their response time and sleep. This overlap allowed for a deeper analysis of stress and rest responses to explore other factors that might influence performance, providing insights into the underlying variables at play.

4 Participants with sleep hours and measured reaction time similar to non users : P1, P7, P17, P22

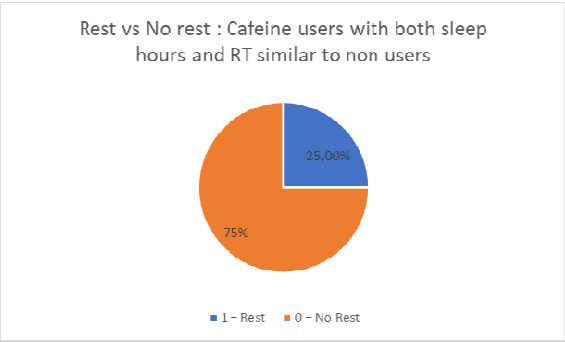


Fig 12:Distribution of Rest Among Participants with No Caffeine Effect on Reaction Time or Sleep

The pie chart shows the distribution of rest among participants who experienced no effect of coffee on their response speed or sleep quality. Seventy-five percent of these participants reported getting little to no rest, while the remaining twenty-five percent indicated some level of rest. This suggests that a large majority of subjects who weren't affected by caffeine had insufficient rest, which may have had a significant impact on their overall performance.

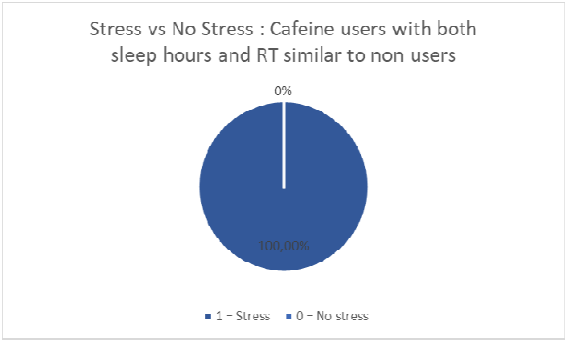


Fig. 13:Stress Distribution in Participants with No Caffeine Impact on Performance or Sleep

The pie chart shows the stress responses of participants who experienced no effect of caffeine on their reaction time or sleep quality. All participants—100%—reported experiencing stress. This suggests that stress could be a major factor influencing their performance, regardless of caffeine intake.

V. DISCUSSION

A. Model Accuracy and Practical Implications

This study aimed to explore how caffeine affects cognitive performance, particularly reaction times and sleep duration, within the context of air traffic control. The results showed that caffeine generally improves reaction times, which aligns with previous research suggesting that caffeine enhances cognitive function (Smith, 2002). The scatter plot of observed reaction times for caffeine users revealed a negative relationship between caffeine consumption and reaction times, confirming findings from earlier studies (Haskell et al., 2005). Similarly, the predictions made by the 2B Alert Web system followed this negative trend, supporting the model's ability to accurately forecast reaction time performance (O'Brien & Hunter, 2020).

However, despite these general patterns, some participants showed no significant change in their reaction times or sleep durations due to caffeine intake, raising questions about individual differences. The scatter plot showing caffeine users' sleep habits revealed that some individuals' sleep durations remained unchanged, even with caffeine consumption. This suggests that other factors, like individual metabolic rates or contextual variables, might have a greater impact on performance and sleep than caffeine alone (Tan & Lee, 2018).

To dive deeper into this, we focused on the participants who showed no significant effects of caffeine on either response time or sleep. The Venn diagram revealed that this group had distinct patterns of stress and rest. Seventy-five percent of these participants reported not getting enough rest, and 100% said they were stressed. This highlights the importance of considering non-caffeine factors, such as stress and rest, when assessing cognitive

performance. The lack of rest in most participants who showed no caffeine effect suggests that insufficient rest could be a key factor in performance, regardless of caffeine intake (Sadeh, Gruber, & Raviv, 2003).

B. Other factors Influencing Performance

Several factors can also influence cognitive performance:

Individual Differences: Genetic factors, baseline cognitive abilities, and sensitivity to caffeine can all affect how well the model predictions align with real-world performance (McLellan, Caldwell, & Lieberman, 2016).

Environmental Variables: Things like sun exposure, stress levels, and physical activity can also impact performance, and these factors should be incorporated into more advanced models (Silva & Neri, 2009).Future models should explore non-linear effects and the combined impact of caffeine with other stimulants (Dopamine, 2011).Finally, the limited sample size in this study may restrict how widely the results can be applied (Bender & Shaughnessy, 2013).

C. Future Research Directions

Future research should focus on the following areas:

Integrating Additional Variables: Incorporating genetic, environmental, and psychological factors to improve the accuracy of performance models (O'Connor & Clark, 2020).

Exploring Non-Linear Effects: Investigating the complex, non-linear relationships between caffeine, sleep, and cognitive performance (Tan & Lee, 2018).

Implementing Practical Applications: Using advanced models in real-world scenarios to refine techniques for optimizing performance (Verster & Neve, 2014).

Expanding Sample Size: Increasing the sample size to make the findings more robust and applicable to broader populations (Hunter & McElroy, 2012).

Leveraging Advanced Prediction Methods: Utilizing modern prediction techniques, such as machine learning models, to improve forecasting accuracy (Driskell & Morrow, 1999).

VI. CONCLUSION

In conclusion, our data support the idea that caffeine improves cognitive performance, as shown by the negative relationship between caffeine intake and reaction time (Haskell et al., 2005). However, the results also suggest that caffeine's effect on sleep is not consistent, as some individuals didn't experience changes in sleep duration despite consuming caffeine (Smith, 2002). When examining stress and rest in those who didn't show any caffeine-related effects, it became clear that stress and lack of rest could significantly impact performance. This is particularly important in air traffic control, where cognitive performance is critical for safety and efficiency. Air traffic controllers often work in high-pressure environments, and factors like stress, rest, and caffeine intake can influence their vigilance and reaction times (Kuisma & Oksanen, 2006). Future research should delve deeper into these factors, especially in the aviation industry, and take into account environmental influences to study the interactions between caffeine, sleep, stress, and cognitive performance in high-stake fields like air traffic control. (O'Brien & Hunter, 2020)

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UNSUPERVISED MACHINE LEARNINGINSIGHTSINTO HEREDITARY DISORDERS THROUGH GENOMIC PROFILING

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Abstract- Through genomic profiling researchers identify unique genetic sequences which exist specifically in each family structure. Genomic clustering methods in this proposed analysis distinguish separate genetic groupings or patterns which demonstrate strong inheritance connections between parents and children's genomic data. The clustering model demonstrates strong evidence for its reliability and precision by showing both familiar genetic inheritance patterns alongside unexpected genotypic outcomes such as (TT) whereas certain children illustrate possible de novo or non-Mendelian genetic inheritance patterns. These genomic anomalies compound the inherited genetic tendencies and provide unique perspectives into uncommon genomic patterns enabling exceptional health predictions of cystic fibrosis and achondroplasia. Machine learning algorithms reveals methods to discover patterns inside complex genomic datasets and generate meaningful predictions. These findings support individualized treatment through cantered clinical solutions based on genomic features while tracking family genetic profiles. The approach enables early disease detection followed by targeted treatments while developing preventive strategies for reducing risk. Furthermore, those findings can aid the genetic counseling and foster the development of own family-unique healthcare strategies, establishing a new healthcare paradigm that adapts to the genetic characteristics of each member of the family. The integration of this genomic clustering version into medical practices can revolutionize healthcare via bridging the gap among genomics and real-world medicine, contributing to advancements in predictive healthcare, population genetics, and precision medicine research.

Keywords - Genomic Profiling, Unsupervised Learning (USL), Genomic Clustering, Personalized Healthcare, Autosomal Dominant, Autosomal Recessive

I. INTRODUCTION

A one-size-fits-all approach from the traditional clinical environment has become less efficient since healthcare is evolving toward more personalized care models. This study reveals how genetic insights pair with Machine Learning (ML) to transform personalized healthcare through precision medication alongside genetic-based therapy approaches. [1]. The union of machine learning algorithms with genomic statistics enables pioneers to unravel complex genetic-to-health outcomes connections. This research pursues three main objectives including the development of improved diagnostic and prognostic capabilities and tailored therapies designed for individual patient genetic profiles. [2]. The practice of Machine Learning in genomic precision medicine shows promise to advance customized healthcare through comprehensive genetic disorder understanding [3]. The research focuses on the potential to use Machine Learning algorithms that analyze genetic information for reshaping clinical operations toward individualized and efficient patient treatment systems. Through profound scientific technological advances in genetic precision medication ML achieves new capabilities together with scientific knowledge. [4].

The Human Genome Project (HGP) reached its termination in 2003 and delivered humanity's complete first genomic map.This milestone laid the groundwork for future studies into the links among genetic variations and health, supplying insights into the complexity of human genetics. The HGP stands as one of the most remarkable exceptional scientific achievements. This global collaboration aimed to analyze the entirety of human DNA, or genome, in depth. Its defining achievement—creating the first sequence of the human genome—offered crucial knowledge about the human blueprint, which has enhanced the study in human biology and progressed scientific practices [5]. Figure 1 presents Image of Single Nucleotide Polymorphism in a Human Genome using transmission electron microscope.

Human DNA is built like a microscopic twisted ladder known as a double helix. This iconic shape is formed by two long strands of sugar and phosphate molecules linked together, creating the ladder's backbone. Each rung of the ladder is formed by a pair of nitrogenous bases, which derive in four varieties: adenine (A), guanine (G), cytosine (C), and thymine (T). These hold the key to genetic information in the form of human DNA. Figure 2 presents microscopic double helix from human DNA.

Later, an age of data generation was ushered in by the introduction of high-throughput sequencing technology, which facilitated the creation of massive genetic data databases [6]. When these datasets developed, it became evident how limited existing analytical approaches were, necessitating a paradigm shift. ML has an enormous ability to recognize complex pat- terns and extract important information from these massive genomic data. The merger of ML algorithms with genomics recognized each person's

unique genetic composition and offered a new frontier in customized medicine for individualized diagnostics, medications, and treatments [7].

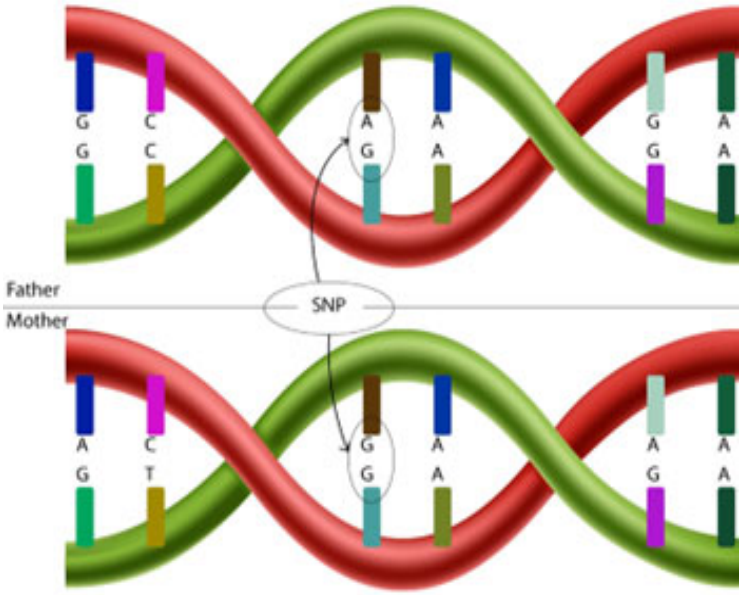


Figure 1: Image of Single Nucleotide Polymorphism in a Human Genome

The key application of ML techniques for genetic research including the development of prediction models for hereditary diseases, and genomic profiling, introduced significant advances in the field [8]. This evolutionary process is far from over since ongoing efforts are made to improve interpretability, optimize algorithms, and handle ethically and privacy related issues [9]. To harness the capacity of ML and comprehend the vision of genomic precision medication, the idea of "genomic profiling" plays a vital role [10]. This involves examining an individual's entire genetic composition, inclusive of DNA sequences, gene expressions, and genetic changes.

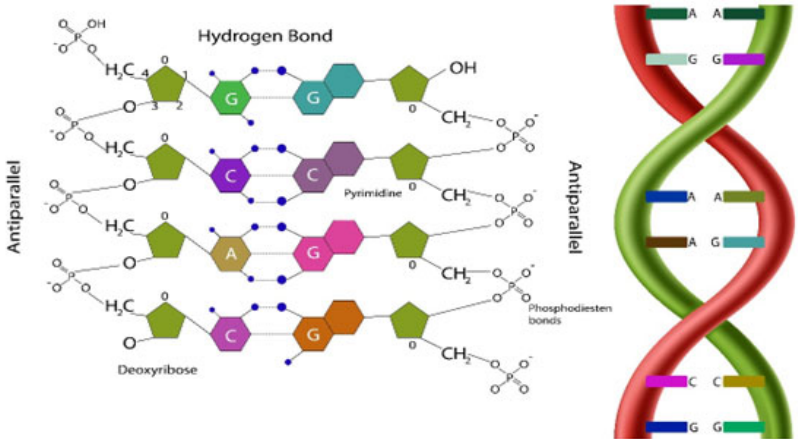


Figure 2: Double Helix Human DNA Structure

Genomic profiling serves because the cornerstone of the personalized healthcare, uncovering the unique genetic pattern that are linked to fitness and disease [3].Moreover, machine learning algorithms offer a complete framework for extracting significant insights and identifying the patterns inside the huge amount of complex data of genetic information. Expanding beyond the intersection of genomics and ML techniques, the concept of "predictive modeling" emerges as a key approach for developing the models that predict health outcomes based on an individual's genetic information [8].

In the realm of unsupervised mastering (USL), clustering algorithms are involved in uncovering the natural pattern in genomic data [9]. The discovery of natural patterns in genomic data relies on clustering algorithms within unsupervised mastering frameworks [9]. Grouping procedures based on genomic properties allow identification of genetic behavior clusters that match these traits between participants. Inside familial genetics these clustering methods help

identify subpopulations that display unique genetic characteristics and patterns of inherited features. This methodology shows diffused similarities and differences between family genetic data to provide new understanding about complex genomic networks within families. Genomic pattern discoveries push our ability to understand inherited traits together with gene-family interactions using genetic predispositions. Research toward identifying genetic markers of inherited medical issues will drive effective targeted genomic medical practices in the future. [10].

II. MATERIALS & METHODS

There are two main phases in the proposed model: first it processes a dataset followed by data preprocessing. Exploratory data analysis follows preprocessing to deliver valuable information about the records. Feature selection methods identify crucial clustering factors following initial feature selection. A subsequent unsupervised learning algorithm executes the clustering process of selected information. To measure cluster quality the results, undergo evaluation. Document analysis to detect genetic patterns leads to subgroup identification of individuals through genetic profile comparisons. The proposed model is depicted in Figure 3.

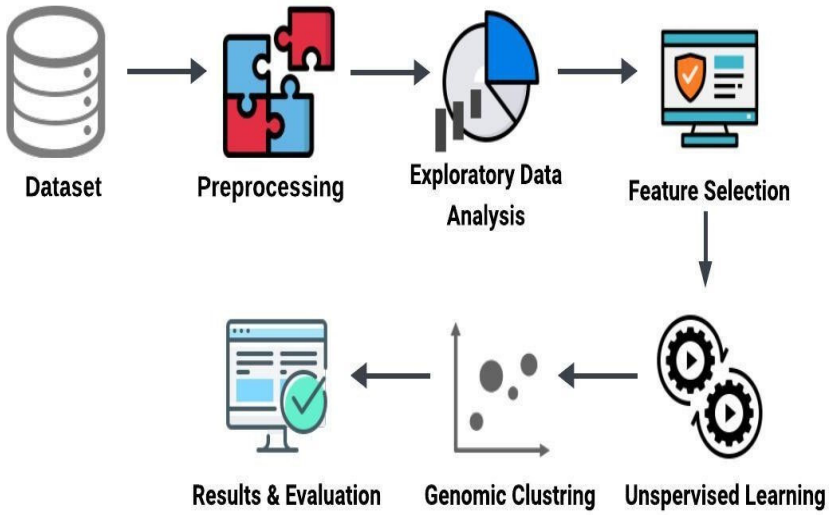


Figure 3: Proposed USL-based Model for Genomic clustering

A. Dataset

Viewed through the scope of whole-genome sequencing, the "Family of Five - Genome Dataset" on Kaggle offers a notable and designated approach into the complicated network of familial genetic relationships, presenting beneficial insights into the hereditary connections and genetic interaction within a circle of family unit. This dataset comprises 5 whole genomes—two from the father and mother and 3 from their child's—observed by means of detailed annotations. The widespread complexity of human genetic information evident in the fact that every genome, representing a single instance, comprises over three billion DNA base pairs.

B. Preprocessing

Three essential characteristics are present in each of the five distinct CSV files representing the five family members that make up the "Family of Five - Genome Dataset" on Kaggle. "Position" pinpoints the location on the genetic map, "Chromosomes" are categorized by 25 unique labels, and the crucial "Genotype" reveals the genetic makeup at each position. However, the "ID" attribute, acting solely as a unique identifier, was deemed superfluous for the intended analysis and discarded. For example, in the "Father Genome," the "Chromosomes" attribute had 25 distinct both numerical and nominal values. The nominal representations were transformed into numerical values. This data harmonization process is applied to standardize this attribute. The attribute "Genotype" comprises 20 distinct values, ranging from the most frequent "GG" with 111990 occurrences to the least frequent "DI" with 33 occurrences. Duplicate data removal was implemented via a two-step process. First, unique identifiers within each file were compared, and redundant instances were eliminated. Subsequent analysis employed checksums to identify identical genetic sequences across files, further streamlining the data for efficient downstream analyses. After the removal of duplicates, the 601802 instances were reduced to 598371 instances in the "Father Genome". The "Genotype" value "X" is assigned to 6616 unlabelled instances. Similarly, the preprocessing was applied to all files of the other four members i.e. "Mother Genome", "Child 1 Genome", "Child 2 Genome" and "Child 3 Genome". The missing values are replaced by mean and mode. This refinement and preprocessing of the dataset were necessary for robust exploration via USL techniques, paving the way for illuminating the intricate genetic relationships woven within the family's

genomes.Figure 4 depict the Attributes of Mother and Father Genome.

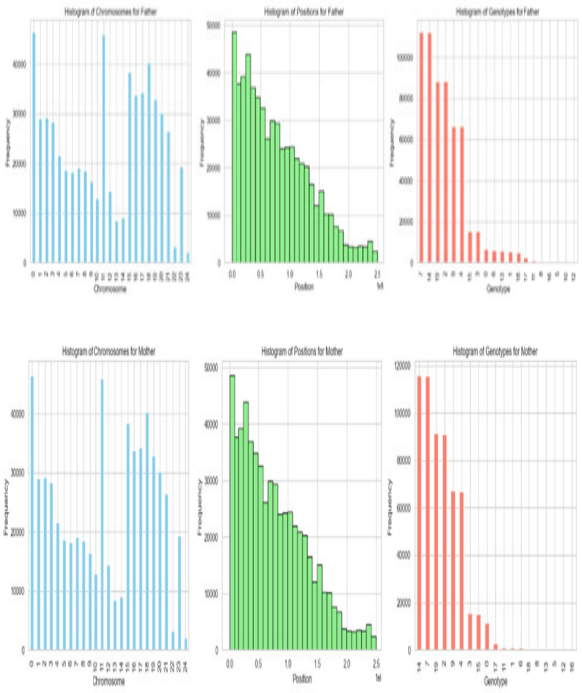


Figure 4: Attributes of Mother and Father Genome

C. Exploratory Data Analysis

After the preprocessing, all the Family of Five genomes were preliminarily analyzed before the subsequent phases. The "Father Genome" is mentioned as an example. The attribute "Chromosomes" has a minimum value of 1 and a maximum value of 25 with a mean of 9.567 and a standard deviation of 6.466. The attribute "Chromosomes" with frequency is illustrated in Figure 5.

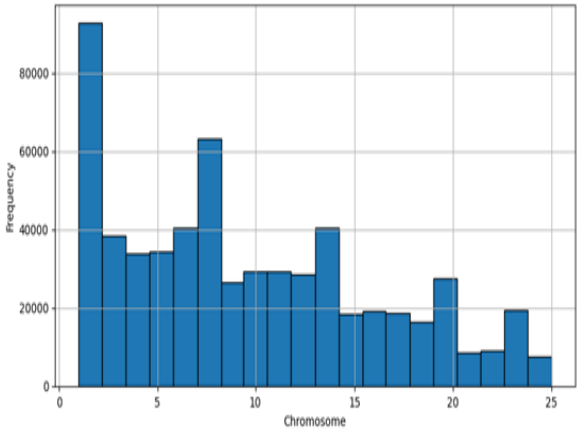
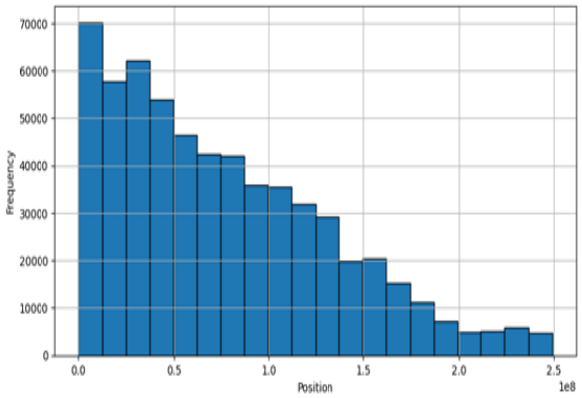


Figure 5: Histogram Attribute "Chromosomes"

The "Position" attribute has to have a minimum value of 3 and a maximum value of 299218992 with a mean equal to 76382309.99 and a standard deviation of 56988227.065. The attribute "Position" with frequency is illustrated in Figure 6.



The attribute "Genotype" is nominal as discussed earlier. The unique value count of the attribute "Genotype" is depicted in Figure 7.

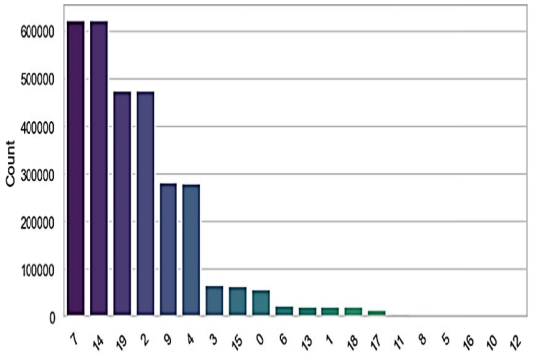


Figure 7: Count of Unique Values in Attribute "Genotype"

D. Feature Selection

Correlations measure the strength and direction of linear relationships between two variables. Knowing how variables are correlated can help to understand how they influence each other. High correlations can suggest potential predictive power. The correlations in the dataset in the form of a heatmap are depicted in Figure 8.

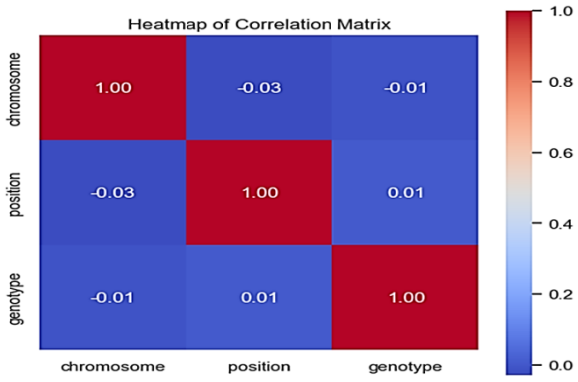


Figure 8: Heatmap to Understand Linear Relationship between Variables

E. Unsupervised Learning

In this data-driven field, unsupervised learning techniques are an effective tool for revealing hidden patterns and structures in large, unlabelled datasets [11]. Unsupervised approaches reveal innate

correlations and clusters among genes and genomic regions, in contrast to supervised learning, where the algorithm is guided by labelled instances [12]. The approach works well for tasks such as finding new gene clusters, locating functional modules, and even detecting genomic markers that may be linked to a disease. Unsupervised learning opens the door for more focused study by revealing hitherto unidentified connections, which might result in advances in condition diagnosis and personalized medication [13-15] Because it can glean insights from the genome's unadulterated symphony, unsupervised learning is a vital tool for deciphering the mysteries of life encoded in its complex genetic code.

F. Genomic Clustering

Genomic clustering is performed on the genomic data of all the family members. The experimental settings for all the family members' genome data were kept identical. The dataset is split into 80 % of training and 20 % test set. The results were obtained using Simple K-means where k = 6 and Euclidian distance. The objective function J is used to calculate the total within-cluster variance. It measures how tightly the data points are grouped in a cluster. This algorithm will try to minimize the J, it finds clusters where data points are close to their own centroids.

$$J = \sum_{i=1}^{k} \sum_{j=1}^{ni} \| xi - \mu i \|^2$$

Where 'k' signifies the number of clusters and 'ni' are the number of those specific data points in the cluster ' I'. The centroid of that cluster which calculates the mean of all data points, represented by μi. This initialize the clusters centroids randomly{ μ1, μ2, …….. μn}, and each point is assigned to the closet centroid cluster Ci. The mean of all points which is assigned to every cluster is used to update the centroid.

$$Ci = \{ x: \| x - \mu i \|^2 \leq \| x - \mu j \|^2, \forall j \neq i \}$$

$$\mu i = \frac{1}{ni} \sum_{x \in Ci} x$$

This whole process of updating of centroid is repeated until no longer is found or change found is below the threshold.

III. RESULTS AND EVALUATION

The "Father Genome" is illustrated in this section as an example. The total number of instances in the "Father Genome" training set is 478696 instances. During the training, the sum of square error within the cluster was recorded as 8.7*104. The training results are illustrated in Table 1.

The clustering analysis discovered 5 distinct clusters, every cluster varying numbers of instances, as specified in Table 1. First Cluster contains 724,255 instances, second Cluster contains 537,500 instances, third Cluster contains 328,386 times, forth Cluster contains 617,403 times, and fifth Cluster contains 129,709 instances. The range of instances of data in every cluster, reflecting the underlying complexity of the genetic facts, with a few clusters containing larger datasets whilst other are smaller. Notably, the model performed 100% accuracy in training, indicating excellent performance in distinguishing between the clusters. The accurate classification throughout all clusters demonstrates the robustness and reliability of the model in identifying genetic patterns. These findings emphasize the effectiveness of the model and its ability for identifying complex genetic relationships, providing a promising basis for destiny applications in genomic studies and personalised medicine. Clustered Instances Test Results shown in Figure 9.

Cluster #	Instances	Chromosomes	Position
Cluster 0	724255	10.767260	4.360147e+07
Cluster 1	537500	12.223165	1.179942e+08
Cluster 2	328386	13.952984	1.623886e+08
Cluster 3	617403	9.816645	7.928058e+07
Cluster 4	129709	5.667901	2.190636e+08
Cluster 5	717278	11.894697	1.357274e+07

Table 1: Father Genome Training Results

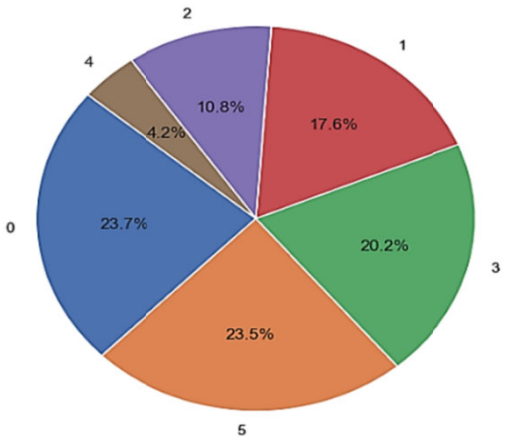


Figure 9: Clustered Instances Test Results

IV. DISCUSSION AND FINDINGS

The results demonstrated that the suggested model we used had a 100% accuracy rate on the test set is far higher than the baseline methods that were previously

offered. Thecluster results of all family members' data is depicted in Table 2.

This result shows that in the first cluster father pass "G" allele and mother can pass on either the "A" or "G" allele to her children. While child-1 inherits ‘A’ allele from the mother and ‘G’ from the father, child-1 is heterozygous (AG) and chil-2 and child-3 both inherited from mother and father so they are homozygous dominant (GG), which means they will have the dominant trait.

Cluster #	Father	Mother	Child -1	Child -2	Child -3
Cluster 0	GG	AG	AG	GG	GG
Cluster 1	CC	CT	CC	TT	TT
Cluster 2	AG	GG	AG	GG	GG
Cluster 3	AA	AA	AA	TT	TT
Cluster 4	GG	AG	GG	AA	AA
Cluster 5	AA	AA	AA	TT	TT

Table 2: Genome Training Results of Clusters

This result shows that in the first cluster father pass "G" allele and mother can pass on either the "A" or "G" allele to her children. While child-1 inherits ‘A’ allele from the mother and ‘G’ from the father, child-1 is heterozygous (AG) and chil-2 and child-3 both inherited from mother and father so they are homozygous dominant (GG), which means they will have the dominant trait. If the gene is autosomal dominant, then only one copy of the dominant allele ‘G’ is required to express the trait. Child-2 and Child-3 (GG) would both show the dominant trait but Child-1 (AG) express the trait of one dominant allele ‘G’. In this cluster Father (GG) and Mother (AG) are both carriers of the gene.

If the disease is autosomal dominant, all three children (Child-1, Child-2, and Child-3) will show the disease or trait because only one copy of the altered gene is enough to cause the disorder and an affected individual has a 50% chance of passing the altered gene to each child, regardless of the child's gender. Autosomal dominant disorders include Neurofibromatosis Type-1 (NF1), which is a common genetic disorder originate tumors to form on the nerve tissue, Huntington's disease is a neurodegenerative disorder causes progressive motor dysfunction, cognitive decline, and psychiatric issues, Achondroplasia is a form of dwarfism, resulting from a mutation in FGFR3 gene, and Marfan syndrome is a connective tissue disorder that affect the heart, vessels, eyes, blood, and skeleton [21].

If the gene is autosomal recessive, two copies of the recessive allele ‘A’ are required to explicit the trait. Child-1 (AG) inherits one ‘A’ from the mother and one ‘G’ from the father, so they may be heterozygous and a carrier and no longer showing the ailment however child-1 can pass the allele. Child-2 and child-3 (GG) inherit the ‘G’ allele from both parents and do not specific the disease but they can also be the carries however do not express the trait. This pattern regularly skips generations, with carriers passing the gene without expressing the disease themselves. Examples of autosomal recessive problems encompass cystic fibrosis which is a genetic problem affecting the lungs, pancreas, liver, and intestines, causes due to the mutations inside the CFTR gene, Tay-Sachs Disease is a neurodegenerative disorder, Phenylketonuria (PKU), which is a metabolic sickness in which the human body cannot break down the amino acid phenylalanine, leading to cognitive disabilities if untreated, and sickle cellular Anemia which is blood disorder wherein red blood cells tackle a sickle form, leading to blockages in blood vessels[18].

In the second cluster Father (CC) is a Homozygous and he does now not have the recessive allele and Mother (CT) is Heterozygous and contains one normal allele ‘C’ and one recessive allele ‘T’. Child-1 (CC), Inherited the ‘C’ allele from both mother and father so Child-1 will be unaffected. Child-2 (TT) and Child-three (TT) Inherited most effective the ‘T’ allele from the mother and no allele from the father which indicates a de novo mutation inside the stated genotypes. Diseases following this inheritance sample are categorized as autosomal recessive disorders. For a child to be affected, that one need to inherit two copies of the recessive allele (TT). Expected ailments consists of Cystic Fibrosis, Sickle Cell Anemia, and Tay-Sachs Disease. This study [17] discusses the genotypes inside the GJB2 gene, where CC represents the homozygous genotype, CT represents the heterozygous carrier, and TT the homozygous mutant related to the hearing loss.

Third cluster is consistent with autosomal dominant inheritance, ‘A’ allele is associated with the dominant trait or disorder. In this cluster Father (AG) is a Heterozygous who is the carrier of one normal allele ‘G’ and one dominant allele ‘A’ and Mother (GG) is Homozygous for the normal allele without dominant trait. Child-1 (AG) Inherited the ‘A’ allele from the father and the G allele from the mother which shows Child-1 affected by the dominant trait, Child-2 (GG) and Child-3 (GG) Inherited the G allele from mother and father so they're not effected. In such conditions, best one copy of the altered gene (A) is enough to cause the disease. These diseases include Achondroplasia, it is a form of short-limbed dwarfism resulting from mutations within the FGFR3 gene. Individuals with one mutated replica (AG) showcase

the circumstance, at the same time as those with regular copies (GG) [22]. Marfan Syndrome is a disorder often resultant from mutations in the FBN1 gene, Huntington's Disease is a neurodegenerative disorder caused by expansions in the HTT gene. A study [16] discusses how specific mutations in the FGFR3 gene lead to achondroplasia, an autosomal dominant disorder.

This genotypic distribution aligns with an autosomal dominant inheritance sample, where the presence of a dominant allele 'A' results in the expression of the related trait or disease. This pattern is found in various genetic conditions, including achondroplasia, that's connected to the mutations within the FGFR3 gene.

In forth cluster a few exciting questions arises Under ordinary Mendelian inheritance policies:

- If each of the parent are (AA), the child must inherit one A allele from each, making all offspring AA.
- The presence of (TT) genotypes in the Child-2 and Child-3 suggests both a de novo mutation, a potential genotyping error, or some form of non-Mendelian inheritance.

If the (TT) genotype arose due to spontaneous mutations in each alleles at some point of early development in Child-2 and Child-3, this can cause genetic problems as a result of homozygous mutations in those specific genes. Expected Diseases with autosomal recessive inheritance appear if the mutation is on a gene critical for some certain traits (e.g., metabolic problems or rare syndromes). Non-Mendelian Inheritance consist of two mechanisms, first one is Uniparental Disomy (UPD) occurs wherein a child inherits two copies of a chromosome or a part of a chromosome from one parent. This is also linked to disorders like Prader-Willi syndrome or Angelman syndrome. Second mechanisms is Somatic Mutations or Mosaicism might also have took place post-zygotically (at some stage in development), leads the differences between germline and somatic cells.

The diseases that would align with this state would probably be uncommon rare genetic disorders. If the mutations affect specific genes, some illnesses might consist of the following disorders like achondroplasia or hypochondroplasia, usually autosomal dominant, however if mutations occur de novo instances are possible. If mutations spontaneously take place in the CFTR gene, it could lead to cystic fibrosis. Smith-Magenis Syndrome (RAI1 Gene) related to de novo mutations. Rett Syndrome (MECP2 Gene) takes place due to spontaneous mutations within the MECP2 gene.

The presence of TT genotypes in Child-2 and Child-3, in which the parents having (AA) genotypes, is exceptionally unusual beneath Mendelian rules. The most probably [19] diseases are linked to the such mutations fall into the class of uncommon rare genetic disorders, frequently affecting genes like FGFR3 will cause excessive cell proliferation, leading to most cancer and skin overgrowth [paper: The paradox of FGFR3 signaling in skeletal dysplasia: Why chondrocytes growth arrest while other cells over proliferate Author: Pavel Krejci], CFTR or others associated with metabolic or developmental syndromes. Further genetic checking out or validation of the records would be needed for the confirmation in this case.

Autosomal recessive inheritance is also being followed by the fifth cluster, as well as carries the instances of non-Mendelian or mutations. Father (CG) is a Homozygous for the 'G' allele, so he can only pass on G allele and Mother (AG) is a Heterozygous who carries one 'A' allele and one 'G' allele. Child-1 (GG) can Inherit 'G' from both parents and Child-2(AA) and Child-3(AA) Inherited 'A' from the mother which increases the possibility of De novo mutation in the father's germline or Uniparental disomy. Diseases fall under autosomal recessive disorders getting two copies of the recessive allele (AA) are: Sickle Cell (Behl n.d.)Disease (HBB Gene) caused by mutations in the HBB gene, Cystic Fibrosis (CFTR Gene) caused by mutations in the CFTR gene as it is realized that individuals who were homozygous for the common F508del variant varied considerably in the severity of lung disease [20], Metabolic Disorders like phenylketonuria (PKU) or Tay-Sachs disease, and Rare Neurological or Developmental Syndromes.

If the Single Nucleotide Polymorphisms (SNPs) are located on different chromosomes or some distant genomic regions, they are not linked, occurred in cluster 4 and 6. The probability of them being inherited collectively at some stage in meiosis may be very low due to the excessive possibility of crossover activities occurring among them in the course of chromosomal recombination. Parallel inheritance of unrelated alleles can also contain the Multiple loci inside genome self-sufficiently produce (AA) or (TT) genotypes in a Mendelian way or Genotype patterns is probably preserved because of evolutionary conservation of the inheritance mechanisms.

IV. CONCLUSION

In conclusion,clustering analysis on the "Family of Five" dataset exposed many significant patterns of inheritance together with important genetic discoveries. Genetic alterations linked to dominant inheritance often make themselves apparent through the simultaneous occurrence of offspring displaying dominant condition and carrier phenotypes in other offspring. The occurrence of (TT) genotypes in particular observed cases indicated potential de novo

mutations or genotyping mistakes or uniparental disomy acting as mechanisms commuting Mendelian inheritance patterns. The genetic transmission proved complicated by these anomalies which offered evidence for associations with diseases like cystic fibrosis and achondroplasia. This research detailed the multilayered relationship between heritable patterns combined with newly generated mutations alongside unusual genetic mechanisms that guide the understanding of genetic issues and familial traits. The discovered familial genomic patterns require further research validation to explore de novo mutations while deepening our comprehension of such inheritance dynamics. Precision medicine development reaches new milestones through improvements in methods used to identify and manage uncommon inherited diseases resulting in individualized therapeutic opportunities.

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★★★

SMART HOME SECURITY SYSTEM WITH APPLICATION INTEGRATION

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Abstract - The "Smart Home Security System with Application Integration" project offers a modern solution to residential security by integrating sensors, , and a central control unit with a web app. This system enables real-time monitoring, instant notifications, and remote management of home security through a user-friendly app. By leveraging cloud services for data storage and processing, the system ensures reliability and scalability. The project enhances home security with convenient, accessible technology, providing users with improved safety and peace of mind.

Keywords - Smart Home Security, App Integration, Real-Time Monitoring, Home Automation, IoT Security, Mobile Applications, Cloud Computing, System Architecture, User Experience.

I. INTRODUCTION

In today's connected world, ensuring the safety and security of homes is more important than ever. The market offers a wide variety of home security systems, many of which use sensors like motion detectors, cameras, and gas leak monitors. However, the cost of purchasing and maintaining these physical devices is often prohibitively high. This research explores the possibility of creating a virtual smart home security system that simulates real-world sensors to provide a cost-effective alternative. The project provides a user-friendly and safe way to monitor different areas of a home's environment by combining these virtual sensors with a web application. This project's primary goal is to create an effective system that monitors important parameters, transmits the data to a web application, and uses cutting-edge security features to safeguard the data.

This literature review seeks to synthesize and analyze existing research findings on smart home security systems with a focus on app integration. By examining current studies and technological advancements, the review aims to identify key knowledge gaps and unresolved issues in the field. It will explore various aspects such as system vulnerabilities, data protection measures, and user privacy concerns. The evaluation will also suggest possible lines of inquiry for further study to tackle these issues, with the ultimate goal of improving the security and dependability of smart home security systems. More reliable and safe smart home security systems will be developed as a result of this thorough investigation.

II. LITERATURE SURVEY

In order to improve intrusion detection in Internet of Things-based smart home security systems, machine learning models have been investigated. The DS2oS dataset was used to assess the performance of several methods, including Random Forest, Naive Bayes, and J48. According to the study, Random Forest had the best accuracy (99.42%) in detecting intrusions while balancing computational efficiency, making it suitable for IoT devices with limited resources. This work emphasizes the potential of optimized machine learning approaches to address security vulnerabilities in IoTenvironments[7].

A thorough analysis of Smart Home Systems (SHS) looked at new developments in fields including artificial intelligence (AI), sensors, and the Internet of Things (IoT). In order to improve system performance in areas like energy efficiency, security, and elder care, a variety of technology approaches were examined, including wireless sensor networks, multiagent systems, and machine learning. The increasing influence of smart home technology on daily life is shown in the improvements in SHS, which improve automation and provide a safer, more comfortable living environment [5].

The integration of AI models has been examined to enhance smart home design, specifically focusing on optimizing energy usage, automating daily functions, and improving comfort in living spaces. AI-driven systems can learn from user behavior to adjust settings like lighting, temperature, and security, creating a more personalized and efficient environment. This research emphasizes the potential for adaptive smart home features that cater to user preferences, promoting both convenience and energy savings[3].

A hybrid smart home security system was devised that integrates anomaly detection with face recognition using logit-boosted CNNs.The hybrid model, combining LR, gradient-boosted classifiers, and CNNs, aims to improve anomaly detection for sensor data. The advantages include multi-class

anomaly classification, adaptive learning, and user behavior profiling, all contributing to enhanced security in smart homes. Future research directions focus on incorporating transfer learning and enhancing generalizability[12].

Using the Internet of Things, a smart home automation system was created to improve security and manage household equipment. To detect gas leaks, intrusions, and fires, this system combines a GSM module, an Arduino ATMEGA328P microprocessor, and a number of sensors, such as a motion sensor (PIR), flame sensor, and gas sensor (MQ2). The system sends alerts via SMS through the GSM module and activates an audible alarm. Users can control appliances remotely through text commands, providing both automation and security. Achieving an average precision of 94.44%, the system is low-cost and energy-efficient, with future improvements aimed at incorporating computer vision to reduce false alarms[4].

To fix security flaws in earlier protocols, a lightweight and safe authentication mechanism for Internet of Things-based smart homes was put forth. A home gateway, smart gadgets, mobile users, and a registration authority are all part of the system model. The protocol enables safe mutual authentication, session key security, and resistance to replay, impersonation, and session key disclosure attacks by relying solely on one-way hash functions and XOR operations. The protocol's appropriateness for resource-constrained smart devices in smart home scenarios was demonstrated by both formal and informal security studies. Improving security and realistic deployment in real-world settings are future directions [11].

Using technologies like GSM, IoT, Bluetooth, and PIC microcontrollers with ZigBee modulation, smart home automation systems prioritize control, monitoring, and security. This study highlighted the capabilities and limitations of each approach: GSM allows SMS-based control and alerts,IoT enables extensive remote monitoring and control via Wi-Fi and sensors, and PIC with ZigBee enables short-range communication with voice command support. Each system is designed to enhance home security, support automation, and assist vulnerable users, though limitations like GSM signal dependency, Bluetooth range, and sensor reliability were noted. The study concluded that IoT is the most versatile due to its remote accessibility and minimal equipment needs, suggesting it as the optimal choice for smart home applications[16].

It was suggested to implement a smart home automation system that makes use of the Internet of Things (IoT) to automate, monitor, and control household appliances. The system, named qToggle, integrates sensors and actuators, primarily using ESP8266 chips and Raspberry Pi boards, to support various applications including temperature control, lighting, security, and energy management. The system enables remote access and control through a smartphone app and supports voice control using Google Assistant and Amazon Alexa. With real-time feedback and flexible configuration, the system is user-friendly, scalable, and designed to be cost-effective and sustainable by integrating solar power options. Future developments include humidity monitoring and video surveillance integration[15].

A smart home safety and security systems developed with the Arduino platform was conducted. The study analyzed 63 research papers published between 2014 and 2019 to identify key applications, enabling sensors, system architectures, and challenges faced by these systems. The research highlighted common use cases like intrusion detection, fire detection, and gas leak monitoring. It underscored the widespread use of the Arduino Uno and Mega boards and detailed various system architectures and communication methods, such as GSM and WiFi. The study also addressed challenges like power outages, device failures, and security vulnerabilities while suggesting future research on enhancing user satisfaction and system extendability[13].

To improve home safety, a smart home security system that makes use of the Raspberry Pi platform, IoT, and face recognition was suggested. To keep an eye on the home entrance, the system combines passive infrared (PIR) sensors, ultrasonic sensors, and a Pi camera. To identify people at the entrance, face recognition is done using the Local Binary Pattern (LBP) technique. If an unfamiliar face is detected, the system alerts the homeowner by sending an email with the intruder's photo. The system’s design supports low power consumption and modular replacement of components, contributing to a cost-effective and scalable home security solution[6].

A smart home automation system utilizing the Internet of Things for remote monitoring, control, and security was proposed. The system incorporates Raspberry Pi 3, various sensors, and a Pi camera to detect intrusions andmonitor environmental conditions. Upon detecting an intruder, the camera captures an image and sends it to the homeowner via email. Users can control devices through multiple interfaces, including the internet, smartphone app, voice control, and electrical switches. The system provides rapid updates and is designed to be low-cost, flexible, and easily installable. Future improvements include live video streaming and enhanced system generalizability[9].

A Smart Home Security System designed to enhance convenience and security through Internet of Things

connectivity was developed. The system utilizes NodeMCU, a variety of sensors, and a camera to monitor home environments and allow remote control of devices like lights, air conditioners, and locks. It enables users to control appliances via a mobile app, voice commands, and motion sensors. The system can also recognize faces, capturing images to differentiate between authorized and unauthorized users. Future enhancements aim to improve automation and reliability, providing users with greater flexibility and security in managing their home environments remotely[10].

A smart home security system that enhances traditional IoT-based security by incorporating co-monitoring features was proposed. The system uses Role and Event-Based Access Control (REBAC) to allow temporary, emergency-based access to IoT devices for trusted individuals, like neighbors or relatives, when the homeowner is unavailable. Through the "ThingZone" prototype, users configure device access permissions for different roles, enabling quick responses to physical and cyber threats, such as fires or unusual network activity. The pilot study highlighted users' preference for limited, temporary access to maintain privacy, with future improvements focusing on integrating machine learning and data analytics for enhanced threat detection[2].

IoT-based smart home systems with a focus on enhancing home security through connected devices were reviewed. The system incorporates Raspberry Pi, Arduino controllers, and sensors like PIR for motion detection, temperature, and smoke sensors, among others, to monitor and secure home environments. Communication between devices utilizes various protocols, including AMQP, SMTP, and HTTP, enabling remote monitoring via mobile apps and email alerts. This study emphasizes IoT's role in automating security responses to potential intrusions and environmental hazards. The system's flexible architecture supports additional sensors, aiming for real-time response, low- and privacy measures, ensuring better interoperability among devices, and fortifying systems to withstand cyber-attacks. The conclusion reinforces that while the integration of IoT, AI, and cost deployment, and energy efficiency[1].

An Internet of Things-based smart home security set-up aimed at providing cost-effective, low-power home monitoring was proposed. The system utilizes an Elegoo Mega 2560 microcontroller, Raspberry Pi 2, RF transmission, and magnetic reed switches to detect door events. When a door opens, the system logs the event and sends it to a server, which can be accessed by an Android app for real-time monitoring. Communication involves RF signals for local data transmission, HTTP POST requests to a NodeJSserver, and GET requests from an Android application.[8].

An IoT-based home security system aimed at enhancing accessibility forphysically disabled individuals, and children was presented. The system uses Bluetooth connectivity to enable remote control of home devices via smartphones, employing various input methods, including voice commands, body gestures, eye recognition, and handprint scanning. Future improvements suggested include adding password-based security, integrating malware protection, and further refining gesture and scanner functionalities. This low-cost solution emphasizes user accessibility and ease of use for vulnerable groups[14]

III. SYSTEM ARCHITECTURE

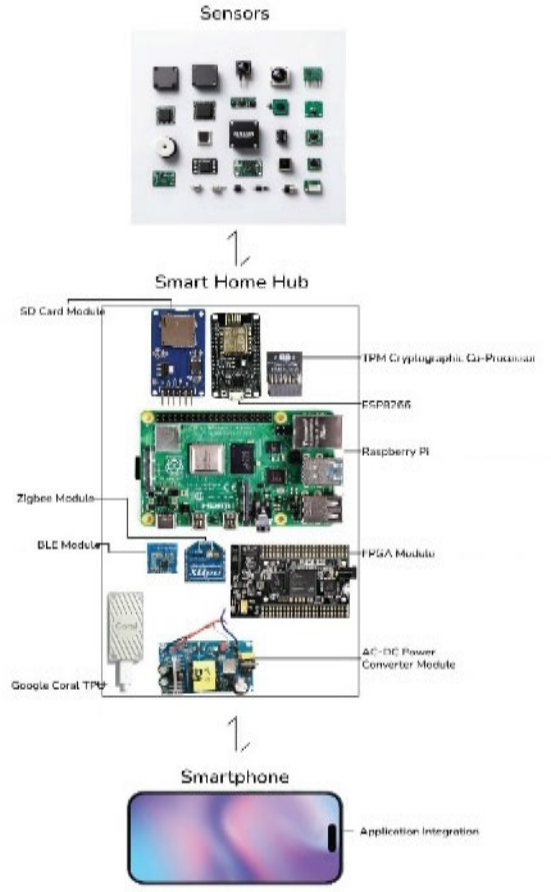


Figure.1. System Architecture

The Smart Home Security System is structured into the following layers:

Sensor Layer:
Virtual sensors are created using Home Assistant, simulating CO2, gas leak, humidity, light, motion, pressure, and sound sensors. These sensors generate

data, which updates every 5 seconds to simulate real-time conditions.
Data Transmission Layer:
The system transfers the sensor data to a web interface using Visual Studio Code and React. This layer ensures secure and efficient communication between the simulated sensors and the user interface.

User Interface Layer:
A React-based web application displays the real-time data from the sensors. The user interface is designed to present sensor information in an intuitive and visually appealing manner.

Security Layer:
Data protection is ensured with advanced encryption (AES-256 and RSA-4096), multi-factor authentication, and end-to-end encryption (E2EE). These security measures safeguard communication and sensitive data.This architecture guarantees effective data flow from the virtual sensors to the user interface, while also ensuring that the data remains secure and protected throughout the process.

IV. METHODOLOGY

4.1 Virtual Sensor Simulation

The to begin with step in the venture included recreating different sensors required for a keen domestic security framework. Given the imperatives of tall costs for real-world sensors, Home Assistant was chosen as a appropriate stage to mimic sensor information in a virtual environment. Using YAML (YAML Ain'tMarkup Language) code, the taking after sensors were simulated:

CO2 Sensor: Recognizes CO2 levels in the environment.
Gas Spill Sensor: Identifies the nearness of perilous gasses like methane or propane.
Humidity Sensor: Measures the relative mugginess in the environment.
Light Sensor: Screens the concentrated of light.
Motion Sensor: Identifies development inside the assigned area.
Pressure Sensor: Screens changes in air pressure.
Sound Sensor: Captures sound levels in the home.
To reenact real-world information, mechanization scripts were made to upgrade the sensor values each 5 seconds. The information produced by these sensors mirrors real-time natural conditions and is utilized in the web application.

4.2 Data Transmission to Web Application

Once the virtual sensors were set up, the next step was to integrate them with a web application to display and monitor the sensor data. This required both front-end and back-end development. Visual Studio Code was chosen for coding the application due to its flexibility and support for multiple programming languages.The front end of the web application was developed using React.js. Effective data rendering and interaction were made possible by React's component-based architecture. For the back-end, the data was transmitted via an API to the web app, allowing real-time updates to be displayed.During the development process, several challenges arose, including CORS (Cross-Origin Resource Sharing) errors, which were eventually resolved after extensive troubleshooting. After overcoming these obstacles, the sensor data was successfully transferred to the web application.

4.3 Web Application Design and User Interface

Following the successful integration of data, the next focus was on enhancing the web application’s design and user interface. The goal was to create an intuitive, user-friendly platform where users can view the status of all virtual sensors in real-time. The application was styled to provide clear and concise visual feedback for each sensor, with color-coded indicators to represent the sensor’s status (e.g., green for normal, red for critical levels).

V. SECURITY FEATURES

An essential component of any smart home security system is data security. Several cutting-edge security measures were incorporated into this project to guarantee that the data was shielded from manipulation and unwanted access.

5.1 Advanced Encryption

To protect the sensor data, hybrid encryption was implemented using both AES-256 and RSA-4096algorithms. AES-256 provides fast encryption for large volumes of data, while RSA-4096 ensures secure key exchange between the server and client.

Additionally, post-quantum encryption methods, such as the Kyber algorithm, were included to future-proof the system against potential threats posed by quantum computers.

5.2 Authentication and Authorization

Multi-Factor Authentication (MFA): MFA was implemented to require users to authenticate through multiple channels, including passwords, biometrics (fingerprint or face recognition), and OTPs (One-Time Passwords).By limiting access to the application according to user roles, Role-Based Access Control (RBAC) made sure that only individuals with the proper authorization could view sensitive information or carry out essential tasks.

5.3 Secure Communication

End-to-End Encryption (E2EE) was used to secure data as it travels from the user’s device to the server, making certain that the data can only be read by the sender and the recipient. TLS 1.3 was implemented to

secure all app communications, with forward secrecy to ensure that encrypted data cannot be decrypted in the future, even if the encryption keys are compromised.Mutual TLS (mTLS) was used for internal communication between microservices to ensure that both parties are authenticated.

5.4 Data Protection

Database Encryption: All sensitive data stored in the database was encrypted at rest to prevent unauthorized access.Encrypted Metadata: Even non-sensitive metadata such as timestamps and file names were encrypted to ensure the privacy of all information.Homomorphic Encryption: This advanced form of encryption makes it possible to execute calculations on encrypted data while maintaining the data's security during processing.

5.5 Real-Time Monitoring

A dedicated cybersecurity monitoring page was integrated into the web application to track all security metrics in real-time. The system includes an anomaly detection feature, which alerts administrators of any unusual activity. Additionally, a system health dashboard monitors the performance of encryption protocols and logs security events.

5.6 Advanced Logging and Auditing

Immutable Logs were stored securely using blockchain technology, ensuring that logs cannot be tampered with.Real-Time Logging monitors user activities and alerts administrators of any potential security breaches.

5.7 Zero-Trust Architecture

A Zero-Trust Architecture was implemented, requiring continuous authentication for every access request and enforcing strict granular policy controls to limit access to the least privileges necessary.

5.8 Regular Key Management

Automatic Key Rotation ensures that encryption keys are refreshed regularly.Using cloud-based Key Management Systems (KMS) or Hardware Security Modules (HSMs) for safe key storage provides an additional layer of protection for encryption keys.

5.9 Intrusion Detection and Prevention

The system integrates IDS/IPS (Intrusion Detection and Prevention System) to monitor and block malicious activity.Firewall rules were set up to enforce secure traffic boundaries and protect against unauthorized access.

VI. RESULTS AND DISCUSSION

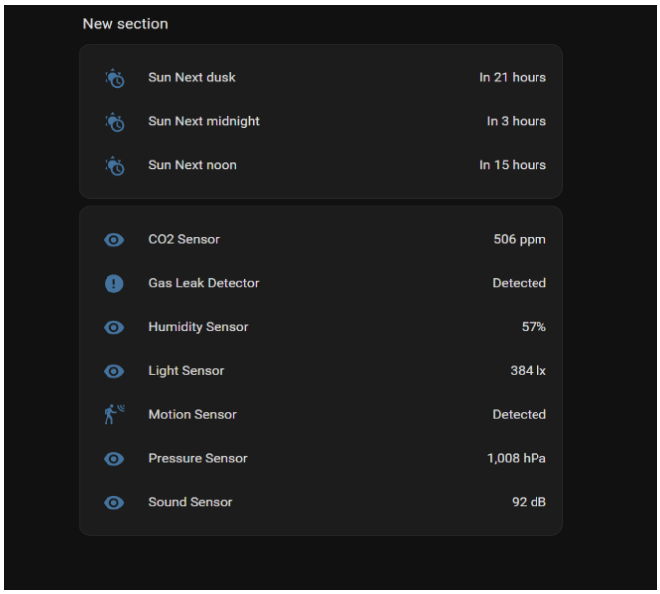


Figure.2.HomeAssistant Dashboard

The output shows the dashboard of the Home Assistant platform, displaying data from multiple simulated sensors. These sensors include:Humidity Sensor, Gas Leak Sensor, Motion Sensor, CO2 Level Sensor, Temperature Sensor,Sound Sensor, Light Sensor, Pressure Sensor.

The dashboard updates sensor readings every 5 seconds to provide real-time environmental monitoring. The simulation successfully integrates multiple sensors and demonstrates their functionality within the Home Assistant framework. These sensors cover various applications, such as safety (gas leak, motion sensors), environmental control (temperature, humidity, CO2 level), and sound or light monitoring. The continuous data feed ensures precise tracking of environmental parameters, critical for smart home automation systems.



Figure.3.Sensor Logs

The output depicts a graphical visualization of sensor data in Home Assistant.

The graph dynamically updates every 5 seconds, offering a clear representation of real-time sensor data trends. This feature allows for effective analysis of temporal changes in environmental conditions. For instance, trends in CO2 levels or sudden changes in temperature can be identified quickly. These visualizations are essential for detecting anomalies, enhancing user comprehension, and enabling swift corrective actions when needed.

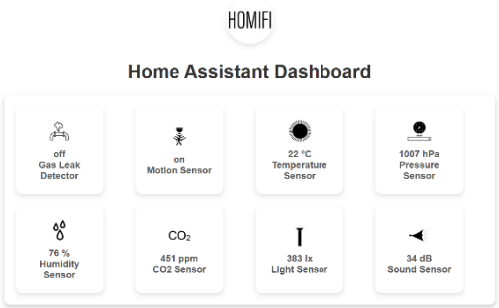


Figure.4. Web App Dashboard

The output showcases the dashboard of a custom-built web application developed using React. This dashboard displays sensor data retrieved from Home Assistant through the REST API.

The web application leverages advanced cryptographic techniques to ensure secure data transfer and storage. These measures include:Advanced Encryption for Data Security:All data transmitted between the Home Assistant platform and the web application is encrypted using protocols such as HTTPS or TLS, preventing unauthorized interception or tampering.Role-Based AuthenticationandAuthorization:Access to the web application is restricted using role-based authentication mechanisms. Users are granted specific privileges based on their roles, ensuring sensitive data is only accessible toauthorizedindividuals.EndtoEndSecureCommunicationChannels:Data is securely transmittedthrough encrypted channels, protecting it from potential cyber threats during transmission

.



Figure.5. Web App Graph

Comprehensive Data Protection Measures:
Techniques such as data masking and secure storage ensure that sensitive information remains protected, even if accessed by unauthorized parties. Real-Time Security Monitoring Dashboard:The application continuously monitors incoming data for anomalies or suspicious activities, ensuring immediate alerts in case of potential security breaches.HardenedandSecureAPIs:The REST APIs used to fetch data from Home Assistant are hardened with additional security layers, such as rate-limiting, validation checks, and token-based authentication, to mitigate risks.Detailed Logging and Incident AuditingSystem:All system activities are logged for auditing purposes, providing transparency and enabling incident investigation if required.Zero-Trust ArchitectureforEnhancedSecurity:Thesystemimplements a zero-trust architecture, meaning every access request is authenticated and authorized regardless of its origin within or outside the network.Regular Key RotationandManagement:Encryption keys are rotated periodically to reduce the likelihood of unauthorized decryption. Secure key management systems are used to handle this process.Intrusion Detection and Prevention Integration:The system incorporates intrusion detection and prevention tools to identify and block any malicious activities. Compliance with Security Standards and Regulations:The project adheres to security standards, such as GDPR and ISO/IEC 27001, ensuring legal compliance and fostering user trust.User-Centric SecurityEducationandAwareness:The project emphasizes user education,ensuring users are aware of security best practices when interacting with the application.
The system guarantees a strong security framework for the real-time display and analysis of sensor data by putting these cryptographic approaches into practice. The React-based interface enhances usability while maintaining data integrity and confidentiality. This combination of user-friendly design and advanced security measures makes the application highly reliable for secure smart home automation.

VII. CHALLENGES AND SOLUTION

Several challenges were encountered during development. Generating realistic data patterns required careful scripting and testing to ensure accuracy. Ensuring seamless communication between Home Assistant and the application was another critical aspect, addressed through REST API optimization. Data security was prioritized by implementing SSL/TLS encryption for all data transmissions. These measures ensured the system's reliability, scalability, and security.

VIII. CONCLUSION

The Smart Home Security System with Application Integration demonstrates that it is possible to create an affordable, secure, and efficient smart home security solution using virtual sensors and advanced security mechanisms. The project successfully integrates sensor data into a web application and employs robust encryption and authentication techniques to guarantee user data security and privacy. As the technology advances, it has the ability to completely change how we think about home security by making it more widely available, scalable, and safe.

FUTURE ENHANCEMENTS

While the current system offers a comprehensive security solution, additional features such as AI and Machine Learning Integration, data storage, and predictive analytics could be incorporated in the future. These would allow the system to better understand patterns and improve security by predicting potential threats based on historical data.

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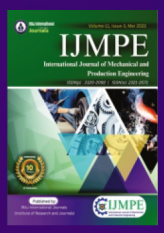
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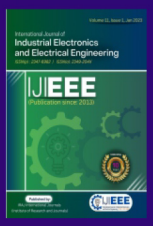
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