

INNOVATIVE APPROACHES IN SUSTAINABLE AGRICULTURE:

CLIMATE-SMART TECHNOLOGIES, BIOTECHNOLOGY, AND RURAL DEVELOPMENTMARKETING STRATEGY

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INNOVATIVE APPROACHES IN SUSTAINABLE AGRICULTURE:

Climate-Smart Technologies, Biotechnology, and Rural Development

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Preface

The rapid growth of the global population, the intensifying impacts of climate change, the depletion of natural resources, and the escalating pressure on food security mandate a fundamental paradigm shift in agricultural production systems. As traditional practices fall short of addressing today's complex socio-ecological crises, sustainability has transitioned from a mere environmental preference into a vital cornerstone for the future of global food systems.

Within this framework, Innovative Approaches in Sustainable Agriculture: Climate-Smart Technologies, Biotechnology, and Rural Development offers a comprehensive, interdisciplinary synthesis of technological transformations, biotechnological breakthroughs, and policy strategies shaping the future of agriculture. This volume bridges diverse domains-spanning autonomous agricultural robotics, climate-smart agro-ecological practices, beneficial soil microorganisms and nanomaterials that enhance plant stress tolerance, sustainable livestock welfare, and rural policy frameworks (such as IPARD and national support mechanisms).

The research presented in this book demonstrates how agricultural innovation extends beyond laboratory boundaries to directly empower smallholder farmers, enhance rural livelihoods, and fortify fresh produce value chains. Positioned at the intersection of biotechnology, digitalization, and climate resilience, this edited volume serves as an essential reference for academics, researchers, policymakers, and industry stakeholders seeking evidence-based solutions for next-generation agricultural systems.

I express my deepest gratitude to all contributing authors for their valuable scientific insights, to the distinguished peer reviewers for their rigorous evaluations and for ensuring the highest academic standards, and to the publishing team for their dedication throughout the production process. May this volume serve as a valuable reference and inspire future research and interdisciplinary endeavors in sustainable agriculture and rural development.

13.10.2026

Prof. Dr. Ahmet ÇELİK

CHAPTER 2

EFFECTS OF TEMPERATURE ON THE PHYSIOLOGICAL CHARACTERISTICS OF ENTOMOPATHOGENIC NEMATODES

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1. INTRODUCTION

Entomopathogenic nematodes (EPNs) belonging to the families Steinernematidae and Heterorhabditidae are recognised as some of the most effective biological control agents used against a wide range of agricultural pests (Stock et al., 1999; Burnell and Stock, 2000; Kary et al., 2009). These organisms are barely visible to the naked eye and spend the majority of their life cycle in the soil, where they encounter and infect susceptible hosts. Upon locating a suitable host, infective juveniles (IJs) enter the insect through natural body openings and release their symbiotic gram-negative bacteria belonging to the family Enterobacteriaceae into the host haemocoel. These bacteria rapidly reproduction within the insect, causing septicaemia and ultimately leading to host death within 24–48 hours (Boemare et al., 1996; Stock et al., 1999; Mahar et al., 2005).

The ability of EPNs to actively search for hosts, together with their sustainability and environmentally friendly characteristics, has established them as important components of Integrated Pest Management (IPM) programmes (Georgis, 1992; Askary and Abd-Elgawad, 2021; Erdoğan and Ulu, 2024). Unlike synthetic pesticides, EPNs pose minimal risks to humans, non-target organisms and the environment. Furthermore, increasing awareness of the adverse effects of chemical pesticides on non-target organisms and ecosystems has enhanced the commercial importance of EPNs and stimulated growing interest in their application as biological control agents (Boemare et al., 1996; Cruz-Martínez et al., 2017; Bütüner and Susurluk, 2023; Yaraşır et al., 2024).

The physiological performance of EPNs is strongly influenced by various abiotic factors; among these, temperature is considered one of the most critical.. Temperature can significantly affect numerous biological characteristics, including survival, infectivity, reproductive capacity, mobility and persistence in the environment (Brown and Gaugler, 1997; Gouge et al., 1999; Chen et al., 2003). As EPNs spend a substantial proportion of their life cycle in soil habitats, fluctuations in temperature directly influence their physiological processes and consequently their efficacy as biological control agents. Both low and high temperatures can alter metabolic activity, energy reserves, host-seeking behaviour and tolerance to environmental stress. Numerous studies have demonstrated considerable variation among EPN

species and isolates in their responses to temperature, indicating differences in thermal tolerance and adaptive capacity (Pervez et al., 2016; El Khoury et al., 2018; Bütüner and Susurluk, 2023; Matuska-Łyżwa et al., 2024; Susurluk and Bütüner, 2024).

In recent years, the increasing impact of climate change on agricultural production systems has intensified interest in understanding the responses of EPNs to environmental stressors. In particular, temperature fluctuations have the potential to directly affect the survival, distribution and biological control performance of EPN populations (Griffin, 1993; Chen et al., 2003; Stuart et al., 2015). Consequently, the identification of temperature-tolerant isolates and the elucidation of physiological adaptation mechanisms associated with thermal stress have become important areas of research for the sustainable utilisation of EPNs in biological control programmes (Bütüner and Susurluk, 2023; Matuska-Łyżwa et al., 2024; Susurluk and Bütüner, 2024).

The aim of this review is to summarise current knowledge regarding the effects of temperature on the physiological characteristics of EPNs, with particular emphasis on survival, infectivity, reproductive capacity and adaptive responses to thermal stress. Furthermore, the implications of temperature-induced physiological changes for biological control applications and future research directions are discussed.

2. Temperature Effects on Entomopathogenic Nematode Biological Activity

Temperature is one of the most important abiotic factors influencing the biological activity, survival, infectivity and reproduction of EPNs. As soil-dwelling organisms, EPNs are continuously exposed to temperature fluctuations that directly affect their physiological processes and biocontrol performance. Environmental temperatures outside the optimal range may impair nematode movement, host-finding ability, penetration success, reproductive potential and long-term persistence in the soil (Hussaini, 2017; Bütüner et al., 2023; Fatimah et al., 2025). Consequently, temperature is considered a key determinant of the efficacy of EPNs in biological control programs. The influence of temperature on EPN activity begins with host-seeking behaviour and mobility. Chen et al. (2003) demonstrated that temperature significantly affected the host-searching ability of several

Steinernema and *Heterorhabditis* species. Reduced mobility was observed at lower temperatures, resulting in delayed host location and penetration. The same study revealed substantial interspecific variation in thermal tolerance, with *Steinernema feltiae* (Rhabditida: Steinernematidae) maintaining infectivity at 10°C, whereas *Heterorhabditis bacteriophora* (Rhabditida: Heterorhabditidae) was only effective at 20°C. Furthermore, penetration into host larvae occurred more rapidly as temperature increased, indicating that thermal conditions strongly regulate the infection process. Temperature also plays a crucial role in determining infectivity and virulence. Gouge et al. (1999) reported that the number of IJs invading insect hosts varied significantly according to temperature, nematode species and host species. Importantly, the temperature supporting maximum infection differed among host insects, suggesting that optimal temperatures for biological control are host-dependent rather than species-specific alone.

Similarly, El Khoury et al. (2018) observed that the highest mortality rates of *Galleria mellonella* (Lepidoptera: Pyralidae) larvae occurred between 15 and 20°C, whereas infectivity declined substantially at lower temperatures. However, some isolates of *S. ichnusae* (Rhabditida: Steinernematidae) and *H. bacteriophora* retained infective capacity even at 35°C, highlighting considerable isolate-dependent variation in thermal adaptation. The interaction between temperature and other environmental factors may further influence EPN performance.

Radová and Trnková (2010) demonstrated that both temperature and soil moisture significantly affected the virulence of *S. carpocapsae* (Rhabditida: Steinernematidae) and *S. feltiae*. While *S. carpocapsae* performed better at 25°C, *S. feltiae* exhibited greater efficacy at lower temperatures and under drier conditions. The authors also reported that reduced soil moisture substantially decreased insect mortality, emphasizing that temperature responses cannot be evaluated independently of other environmental variables. Such findings indicate that successful field applications require consideration of both thermal and moisture conditions. In addition to infectivity, temperature strongly influences nematode development and reproduction.

Pervez et al. (2016) found that attachment, penetration, pathogenicity and multiplication of several EPN isolates were significantly affected by temperature. Maximum larval mortality and IJ production were recorded at

30°C, whereas both parameters declined at 20°C and 35°C. These findings suggest that moderate temperatures promote both successful infection and subsequent reproduction, while thermal stress may limit population development.

Similar observations were reported by Bütüner and Susurluk (2023), who demonstrated that storage temperature and duration significantly affected the morphological and reproductive characteristics of *H. bacteriophora* HBH hybrid strain. IJs stored at 15°C for seven days produced the longest hermaphrodite individuals, the largest egg diameters and the highest reproductive capacity, indicating that storage conditions can substantially influence biological quality. Recent studies have further demonstrated that temperature-induced responses occur not only at behavioural and reproductive levels but also at the molecular level. Using quantitative proteomics, Lillis et al. (2022) showed that storage temperature significantly altered protein expression profiles in *S.carpocapsae* and *H. megidis* (Rhabditida: Heterorhabditidae) IJs. Low-temperature storage promoted the accumulation of chaperone and stress-related proteins, whereas proteins associated with metabolism, cell signalling and oxidative stress responses were differentially regulated depending on species and storage conditions. These findings suggest that EPNs activate complex physiological and molecular mechanisms to cope with thermal stress and maintain survival during prolonged storage.

3. Conclusion

Overall, current evidence indicates that temperature influences nearly every aspect of EPN biology, including movement, host-seeking behaviour, penetration efficiency, infectivity, reproduction and physiological adaptation. However, temperature responses vary considerably among species, isolates and environmental conditions. Therefore, understanding species-specific thermal requirements and adaptive mechanisms is essential for maximizing the effectiveness of EPN-based biological control programs under both current and future climatic conditions

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