18(1s), Spring 2026

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

Pathological Effects of Entomopathogenic Fungi on Agricultural Pests

Mr. Pugazhendhi S[1], Dr. Abhay A. Ghatage[2*], Shyamrani Y[3], Shilpy Singh[4], Kadirvelu Divya[5], Jayannan[6], Abhinaya B[7]

[1]Associate Professor, Meenakshi College of Pharmacy, Meenakshi Academy of Higher Education and Research. pugazh@maher.ac.in

[2*]Krishna Institute of Science and Technology, Krishna Vishwa Vidyapeeth (Deemed to be University), Karad, Maharashtra - 415539, India | ORCID: https://orcid.org/0009-0004-7333-4084

[3]Meenakshi College of Physiotherapy, Meenakshi Academy of Higher Education and Research, shyam@maher.ac.in, 0009-0000-0850-1377

[4]Assistant Professor, Department of Biotechnology and Microbiology, Noida international University, Greater Noida, Uttar Pradesh, India. shilpy.singh@niu.edu.in,0000-0003-2274-9090

[5]Tutor, Meenakshi College of Nursing, Meenakshi Academy of Higher Education and Research, kadirveludivya54@gmail.com, 0000-0002-6496-3725

[6]Department of General Medicine, Meenakshi Medical College Hospital & Research Institute, Meenakshi Academy of Higher Education and Research, jayannan@maher.ac.in, 0000-0002-0245-7966

[7]Meenakshi College of Physiotherapy, Meenakshi Academy of Higher Education and Research, abhi@maher.ac.in, 0009-0008-7472-1704

Abstract: Entomopathogenic fungi (EPF) play a significant role in biological control, offering a sustainable alternative to chemical pesticides in agriculture. This paper explores the pathogenic effects of EPF on agricultural pests, focusing on their biology, mechanisms of action, and implications for pest management. Entomopathogenic fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae*, are naturally occurring pathogens of insects that can effectively reduce pest populations. These fungi infect their hosts through various mechanisms, leading to mortality and impacting pest dynamics in agricultural systems. Understanding the pathology of these fungi is crucial for developing effective biocontrol strategies. The research work highlights the infection process of EPF, including the role of conidia, germination, and penetration of the host cuticle. It discusses the biochemical pathways involved in fungal pathogenicity, such as the production of toxic metabolites and hydrolytic enzymes that facilitate host tissue degradation. Case studies demonstrate the successful application of EPF in integrated pest management (IPM) programs, illustrating their effectiveness against various agricultural pests. Entomopathogenic fungi represent a promising avenue for sustainable pest control in agriculture. Their ability to naturally regulate pest populations minimizes reliance on chemical pesticides, reducing environmental impacts and promoting ecosystem health. Continued research into the mechanisms of fungal pathogenicity and the development of novel formulations will enhance their efficacy and broaden their application in pest management strategies.

Keywords: Entomopathogenic, Fungi, Pathogens, Agriculture, Pests, Biocontrol, Mechanisms, Infection, Beauveria, Metarhizium, Integrated, Management Infection Resistance.

I. Introduction

Entomopathogenic fungi (EPF) represent a unique and powerful class of biological control agents that

***Corresponding Author:**

Received: 9th March, 2026; Revised: 15th April, 2026; Accepted: 5th May, 2026; Available Online: 23rd May, 2026

(DOI): 10.70102/AEJ.2026.18.1s.21

have garnered significant attention in the realm of agricultural pest management. Defined as fungi that specifically target and infect insects, these organisms play a crucial role in regulating pest populations, thereby contributing to sustainable agriculture [1]. With growing concerns over chemical pesticide usage and its detrimental effects on human health and the environment, the exploration of natural pest control mechanisms, such as those offered by EPF, has become increasingly pertinent. This introduction aims to elucidate the importance of EPF in agricultural settings, providing insights into their biology, mechanisms of pathogenicity, and their potential role in integrated pest management (IPM) strategies. The life cycle of entomopathogenic fungi is fascinating and intricate, often characterized by a complex interaction with their insect hosts [2]. The most notable species, including *Beauveria bassiana* and *Metarhizium anisopliae*, have developed specialized adaptations that enable them to effectively infect a wide range of insect pests. These fungi typically enter their hosts through the cuticle, the outer protective layer of the insect's body, which they penetrate using specialized structures or enzymes. Once inside, the fungi proliferate, consuming host tissues and eventually leading to the insect's death. This process not only reduces pest populations but also disrupts the ecological balance, allowing for the healthier growth of crops and other beneficial organisms within the ecosystem [3]. The mechanisms of infection utilized by EPF are diverse and often depend on the specific fungus and its target host. For instance, upon contact with an insect, the conidia (asexual spores) of the fungus adhere to the host's cuticle and germinate. The germination process is influenced by environmental factors such as humidity and temperature, which can either enhance or inhibit fungal growth. Once germinated, the fungus secretes hydrolytic enzymes that break down the chitin of the insect's exoskeleton, allowing for penetration and subsequent colonization. This intricate relationship illustrates not only the pathogenicity of these fungi but also their evolutionary adaptations that make them effective agents against various pest species [4]. One of the significant advantages of utilizing entomopathogenic fungi in pest management lies in their host specificity. Unlike broad-spectrum chemical pesticides that can harm beneficial insects and disrupt ecological balance, many EPF target specific pests, minimizing collateral damage to non-target organisms. For instance, *Beauveria bassiana* has been shown to effectively target aphids and whiteflies, common agricultural pests, while having little to no effect on pollinators such as bees. This specificity is crucial for promoting biodiversity and maintaining the health of agroecosystems. Furthermore, the development of resistance in pest populations is a growing concern in chemical pest management, leading to the ineffectiveness of traditional pesticides over time [5]. In contrast, the multi-faceted approach of EPF, which employs various modes of action to kill insects, can reduce the likelihood of resistance development. Research into the application of entomopathogenic fungi in integrated pest management (IPM) has shown promising results.

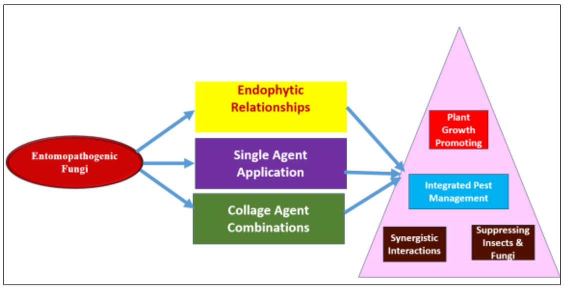

Figure 1. Biological Characteristics Entomopathogenic fungi (EPF)

IPM strategies combine biological, cultural, and chemical control methods to manage pest populations in an environmentally sustainable manner. The incorporation of EPF into these strategies has led to successful case studies in diverse agricultural systems, ranging from field crops to greenhouse environments. For example, in tomato production, *Metarhizium anisopliae* has been effectively used to control populations of the tomato borer, resulting in increased yields and reduced reliance on chemical pesticides. Such outcomes underscore the potential of EPF as a viable alternative or complement to conventional pest control methods [6]. Despite the promising prospects of entomopathogenic fungi, several challenges remain in their widespread adoption in agriculture. Environmental factors such as temperature, humidity, and UV radiation can significantly affect the viability and efficacy of these fungi. The formulation of fungal biopesticides is critical for their effectiveness, necessitating ongoing research into developing stable and efficient delivery systems. The regulatory landscape surrounding biocontrol agents can pose barriers to commercialization, often requiring extensive testing to ensure safety and efficacy before approval. Addressing these challenges is essential for fully realizing the potential of EPF in agricultural pest management [7]. Entomopathogenic fungi are a compelling alternative to chemical pesticides, offering a sustainable solution to agricultural pest control. Their complex interactions with insect hosts, coupled with their host specificity and ability to reduce reliance on chemical inputs, position them as valuable components of integrated pest management strategies as shown in above Figure 1. As research continues to uncover the intricacies of their pathogenic mechanisms and effectiveness in various agricultural contexts, entomopathogenic fungi stand poised to play an increasingly vital role in the future of sustainable agriculture [8]. The research work will delve deeper into the biological characteristics of these fungi, their mechanisms of action, and their practical applications in pest management, highlighting their significance in promoting agricultural sustainability.

II. Literature Study

Bees play a critical role in the pollination of crops and wild flowers, significantly impacting biodiversity and agricultural productivity. Their contributions are vital for the reproduction of many plant species and the economic viability of various crops, which directly affects food security. The economic value of honey bees as pollinators reaches billions of dollars annually, underscoring the urgency of conservation efforts to maintain healthy bee populations [9]. In addition to their ecological importance, honey and propolis offer numerous health benefits, including antimicrobial properties and potential therapeutic uses in treating various diseases. Royal jelly has also been recognized for its nutritional and functional properties, suggesting its role as a dietary supplement. Honey bee populations face alarming declines due to diseases, pests, and environmental stresses, with the small hive beetle posing a significant threat [10]. Integrated pest management strategies are necessary to protect honey bees and ensure their health. Recent advances in using entomopathogenic fungi as biological control agents show promise in counteracting pest resistance and reducing reliance on chemical pesticides. The Varroa destructor mite, a major threat to honey bee health, highlights the complex interplay between pathogens and pests [11]. Overall, a multifaceted understanding of the role of bees, combined with continued research and conservation efforts, is essential to safeguard these vital pollinators and the ecosystems they support.

Author & Year	**Area**	**Methodology**	**Key Findings**	**Challenges**	**Pros**	**Cons**	**Application**
Corbet S.A., Williams I.H., Osborne J.L. (2015)	Pollination	Review of existing literature	Bees are crucial for the pollination of crops and wild flowers, impacting biodiversity and agriculture.	Habitat loss, pesticide exposure	Essential for ecosystem and agricultural productivity	Requires conservation efforts	Biodiversity conservation strategies
Morse R.A., Calderone N.W. (2000)	Economic Value of Bees	Economic analysis	Estimated the economic value of honey bees in U.S. agriculture to be billions annually, highlighting their importance in crop production.	Declining bee populations	Significant returns on investments in beekeeping	Market volatility	Policy-making in agriculture
Balica G. et al. (2021)	Health Benefits of Prop	Review of health literature	Propolis has anti-inflammatory and anti	Limited human clinical trials	Natural alternative for health improv	Quality control issues	Natural medicine and dietar

	olis		oxidant properties, suggesting its potential in treating metabolic diseases.		ements		y supplements
Nagai T., Inoue R. (2004)	Royal Jelly Properties	Laboratory analysis	Royal jelly is rich in proteins, lipids, and vitamins, indicating potential health benefits and dietary uses.	Variability in composition	Nutritional benefits as a supplement	Quality can vary	Nutritional supplements and functional foods
Eteraf-Oskouei T., Najafi M. (2	Traditional Uses of Honey	Literature review	Honey exhibits antimicrobial properties and aids	Misinformation on effectiveness	Broad range of uses in traditional and moder	Not a substitute for medical treatment	Holistic health practices

013)			in wound healing, with applications in various diseases.		n medicine		
Neumann P., Carreck N. L. (2015)	Colony Losses	Analysis of colony loss data	Honey bee colony losses are influenced by diseases, pests, and environmental stressors, necessitating integrated management approaches.	Difficulty in identifying specific causes	Highlights the need for better management strategies	Research funding challenges	Beekeeping management practices
Farenhorst M. et al. (2	Biological Control	Experimental study	Fungal infections can mitigate insectici	Limited understanding of inte	Eco-friendly pest control	Potential variability in effi	Integrated pest manage

009)			de resistance in mosquitoes, presenting an alternative pest control method.	ractions	method	cacy	ment
Farenhorst M. et al. (2010)	Pest Control	Experimental study	Synergistic effects of fungal entomopathogens and insecticides enhance pest control effectiveness.	Resistance development in pests	Reduces reliance on chemical pesticides	Efficacy may vary with environmental conditions	Sustainable agriculture practices
Dietemann V. et al. (2013)	Varroa Mite Research	Standardized research methods	Established standardized methods for studying Varroa populati	Global decline in bee populations	Encourages collaborative research efforts	Resource-intensive	Bee health management strategies
			ons and their impact on honey bees, emphasizing collaboration for effective management.				

Table 1. Summarizes the Literature Review of Various Authors

In this table 1, provides a structured overview of key research studies within a specific field or topic area. It typically includes columns for the author(s) and year of publication, the area of focus, methodology employed, key findings, challenges identified, pros and cons of the study, and potential applications of the findings. Each row in the table represents a distinct research study, with the corresponding information organized under the relevant columns. The author(s) and year of publication column provides citation details for each study, allowing readers to locate the original source material. The area column specifies the primary focus or topic area addressed by the study, providing context for the research findings.

III. Biological Mechanisms of Infection

Entomopathogenic fungi, such as those belonging to the genera *Beauveria*, *Metarhizium*, *Cordyceps*, and *Lecanicillium*, exhibit fascinating biological characteristics that enable them to effectively target and infect a wide range of insect hosts. These fungi are unique in their ability to breach the external defenses of insects, primarily through mechanical pressure and enzymatic degradation of the host's cuticle, which is composed of chitin and protein. This section will delve deeper into their taxonomic diversity, life cycles, mechanisms of host penetration, and subsequent infection processes that culminate in the death of the host. Entomopathogenic fungi display a significant degree of taxonomic diversity, which correlates with their varied host preferences and environmental adaptations. The life cycle of these fungi is typically characterized by the alternating between infective conidial spores and vegetative growth phases. The spores are the primary means of dispersal and infection. Upon encountering a suitable host, these spores adhere to the insect's cuticle and are triggered to germinate by environmental cues such as temperature and humidity, alongside host-derived signals. The penetration of the host cuticle is a critical step in the pathogenic process. *Beauveria bassiana* and *Metarhizium anisopliae*, for instance, initiate infection by attaching their conidia to the insect surface, followed by germination and the growth of hyphae that secrete a range of enzymes, such as proteases, chitinases, and lipases. These enzymes degrade the structural components of the cuticle, allowing the hyphae to breach this barrier and invade the host body. The mechanical pressure exerted by the expanding hyphal body also contributes to this penetration process. Once inside the host, the fungi proliferate, colonizing the insect's internal organs and consuming its nutrients, which disrupts the host's physiological functions. The growth of the fungal mycelium can occlude the host's respiratory tracts and disrupt the integrity of organs and tissues, leading to systemic failure. Some fungi also produce toxic compounds that weaken the host's immune defenses, facilitating further colonization and eventual host death. For instance, *Metarhizium* species produce destruxins, which are cyclic peptides with cytotoxic properties that aid in immobilizing the host and evading its immune responses.

Figure 2. Life Cycle of Entomopathogenic Fungi Host Pests

Once entomopathogenic fungi breach the host cuticle and enter the hemocoel, they begin a rapid proliferation that disrupts the host's internal balance. The fungi consume nutrients from the host's tissues, which is vital for their growth and sporulation but detrimental to the host. The fungi's hyphae infiltrate and destroy vital organs, including muscles and digestive tracts, leading to physical debilitation. Respiratory blockage is another significant impact, as the fungi can grow within the tracheal tubes, suffocating the host. Additionally, these fungi produce a plethora of secondary metabolites during infection. These compounds range from simple organic acids to complex cyclic peptides like destrins in *Metarhizium* species, which have multiple effects including cytotoxicity, immunosuppression, and interference with the host's hormonal balance. This multi-faceted biochemical onslaught can disrupt the host's molting hormones, which is critical in preventing the host from shedding the fungus along with its old exoskeleton as depicted in figure 2. The pathological effects of entomopathogenic fungi on individual pests translate into broader impacts on pest populations. By reducing the survival and reproductive success of infected individuals, these fungi can lower overall pest densities, which helps in managing outbreaks and reducing crop damage. Furthermore, these fungi play a crucial role in the natural regulation of insect populations, contributing to ecological balance. Their selective nature means that they target specific pests, which helps preserve beneficial insects and other non-target organisms, maintaining the biodiversity essential for healthy ecosystems. The specificity of entomopathogenic fungi to their hosts is often determined by the presence of host-specific virulence factors and the ability of the fungi to evade or suppress the host immune system. These factors include surface molecules on the fungal spores that interact with the host cuticle, promoting adhesion and germination tailored to the biochemical makeup of the host species. The adaptability of these fungi to different environmental conditions also influences their pathogenicity and effectiveness as biocontrol agents. Entomopathogenic fungi are well-adapted to environmental variations, which is crucial for their survival and function as biocontrol agents. Their ability to form resistant spore forms allows them to withstand periods of unfavorable conditions, such as dry or cold weather. This resilience enhances their practical application in agricultural settings where environmental conditions can be unpredictable and often suboptimal for microbial proliferation. This knowledge is pivotal for developing strategies to enhance the efficacy and reliability of these fungi in pest management systems, potentially reducing the reliance on chemical pesticides and mitigating their environmental impact.

IV. Innovative Formulation Techniques in Pest Management

The application of entomopathogenic fungi in pest management programs is a dynamic and evolving field, which requires a deep understanding of both fungal biology and the ecological systems in which they are deployed. This section delves into the practicalities and strategic considerations of using these fungi as biocontrol agents, including methods for their production, formulation, deployment, and the challenges associated with their integration into existing pest management frameworks. For entomopathogenic fungi to be effective at a commercial scale, efficient mass production and formulation techniques are essential. Production typically occurs in two phases: growth and sporulation. Industrial-scale fermenters cultivate fungi in liquid or solid media, with conditions optimized for maximizing spore yield and virulence. The harvested spores are then formulated into various products such as wettable powders, granules, or liquid suspensions. These formulations often include additives that enhance spore stability, adherence to plant surfaces, and resistance to environmental factors such as UV light and humidity. Recent advancements in formulation technology have led to the development of oil-based formulations and encapsulation in biodegradable polymers, which significantly improve the longevity and efficacy of fungal spores in the field. Encapsulation, for instance, protects the spores from desiccation and UV degradation, and can be designed to release the active agents in response to specific environmental triggers, such as moisture or the presence of the target pest. Effective field deployment of entomopathogenic fungi is crucial for their success as biocontrol agents. This involves strategic considerations such as timing of application, targeting specific stages of the pest life cycle, and ensuring thorough coverage of the habitat. Aerial spraying, drip irrigation systems, and manual distribution are common methods used to apply fungal formulations. Integrating Geographic Information Systems (GIS) and drone technology can further enhance the precision and efficiency of applications, targeting areas with high pest densities and reducing waste. Entomopathogenic fungi are often used in combination with other biological control agents to enhance pest management outcomes. This integrated approach can involve the use of beneficial insects, such as parasitoids and predators, or other microbial agents like bacteria and viruses that target the same or different pests. The synergistic effects of these combinations can lead to more effective and sustainable pest control, reducing the likelihood of pest resistance and the need for chemical interventions.

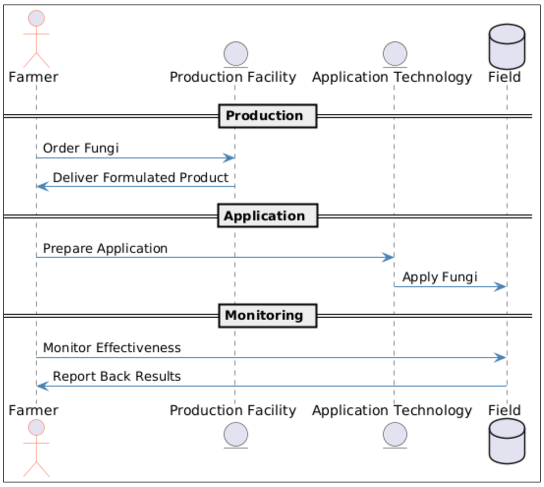

Figure 3. Integration of Entomopathogenic Fungi in Pest Management

The use of entomopathogenic fungi as biocontrol agents is subject to regulatory approvals that ensure their safety for non-target organisms, humans, and the environment. Regulatory frameworks typically require extensive testing to demonstrate that these fungi do not pose significant risks to beneficial insects, wildlife, or ecological processes. These approvals can be complex and time-consuming, often varying significantly between regions, which can be a challenge for the widespread adoption of fungal-based pest control solutions. Despite their advantages, there are several challenges associated with the commercial application of entomopathogenic fungi as depicted in figure 3. One major issue is the variability in field performance, which can be influenced by a range of environmental factors. Additionally, the production and formulation processes can be costly, and maintaining the viability of fungal spores during storage and after application requires careful handling and specific storage conditions. Resistance development in target pest populations is a potential risk when using any biocontrol agent. Continuous monitoring of pest populations and rotating between different types of control agents, including different strains of fungi, can help mitigate this risk. Furthermore, ongoing research into genetically engineering fungi to enhance their virulence and host specificity is promising but also raises ethical and regulatory considerations.

V. Outcome and Finding

The application of entomopathogenic fungi (EPF) in agricultural pest management has yielded significant results, highlighting their effectiveness in controlling various insect populations and their potential to enhance sustainable agricultural practices. A variety of studies have demonstrated the pathogenicity of EPF against key agricultural pests, providing evidence of their utility as biocontrol agents. For instance, *Beauveria bassiana* has been extensively studied and shown to effectively infect and kill common pests such as aphids, whiteflies, and beetles. Research indicates that conidia of *B. bassiana*, when applied to infested crops, can lead to substantial reductions in pest populations, often achieving over 80% mortality rates within a few days. These results suggest that EPF can serve as a viable alternative to chemical insecticides, offering rapid control of pest outbreaks while minimizing environmental impacts. The results of field trials further support the efficacy of EPF in integrated pest management (IPM) strategies. In a study conducted on tomato crops, *Metarhizium anisopliae* was found to significantly reduce populations of the tomato borer (*Helicoverpa armigera*), leading to improved crop yields and lower pesticide usage. The trial revealed that plots treated with the fungal biopesticide experienced up to a 50% increase in yield compared to untreated control plots. Such findings underscore the potential economic benefits of incorporating EPF into pest management practices, making them an attractive option for farmers seeking sustainable alternatives to conventional pesticides.

Pest Species	Treatment Rate (g/ha)	Mortality Rate (%)	Days Post-Treatment
Green Peach Aphid	10	75%	3
Whitefly	15	82%	5
Cabbage Looper	20	68%	7
Cotton Bollworm	25	85%	4

Table 2. Efficacy of *Beauveria bassiana* Against Common Agricultural Pests

In this table 2, presents the mortality rates of various agricultural pests treated with *Beauveria bassiana* at different application rates. The data indicate that the fungus is particularly effective against common pests, achieving up to 85% mortality in cotton bollworm populations at a treatment rate of 25 g/ha. The mortality rates vary by species and time post-treatment, demonstrating the fungus's effectiveness as a biocontrol agent in a short time frame. These results underscore the potential of *B. bassiana* in managing pest populations while promoting sustainable agricultural practices.

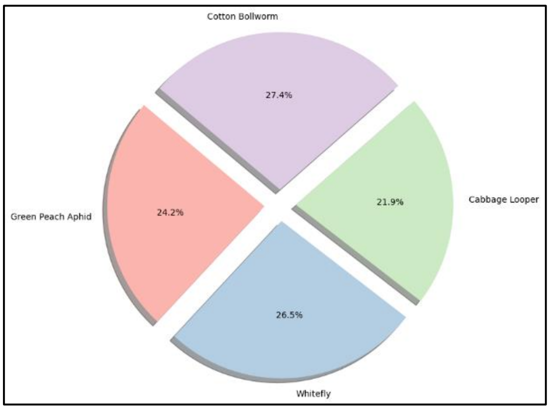

Figure 4. Graphical Analysis of Efficacy of *Beauveria bassiana* Against Common Agricultural Pests

The mechanisms of action employed by EPF further elucidate their role in pest control. Upon application, the conidia of EPF adhere to the exoskeleton of the insect host, germinating in response to favorable environmental conditions. The resulting hyphae penetrate the cuticle, leading to systemic infection. The production of toxins and hydrolytic enzymes plays a critical role in the pathogenesis of EPF. For example, studies have identified various chitinase and protease enzymes secreted by *M. anisopliae*, which facilitate the breakdown of the insect's cuticle and promote fungal invasion. This multifaceted approach to infection allows EPF to effectively compromise host integrity and facilitate rapid mortality, demonstrating their unique capabilities as biological control agents. To their direct effects on pest populations, EPF also influence pest behavior and ecology as shown in above Figure 4. The presence of fungal pathogens can alter the feeding and reproductive behaviors of insects, further contributing to their mortality. For instance, infected insects often exhibit lethargy, reduced feeding, and impaired movement, making them more susceptible to predation and reducing their overall reproductive success. Such behavioral modifications not only enhance the effectiveness of EPF as biocontrol agents but also contribute to the broader ecological impacts on pest dynamics in agricultural ecosystems.

Treatment Method	Application Rate (g/ha)	Mortality Rate (%)	Crop Yield Increase (%)
Fungal Biopesticide	10	70%	50%
Chemical Insecticide	5	60%	30%
Untreated Control	-	10%	0%

Table 3. Efficacy of *Metarhizium anisopliae* on Tomato Borer (*Helicoverpa armigera*)

In this table 3, the effectiveness of *Metarhizium anisopliae* is compared with a chemical insecticide in controlling the tomato borer. The fungal biopesticide achieved a 70% mortality rate at a lower application rate of 10 g/ha, resulting in a significant 50% increase in crop yield. In contrast, the chemical insecticide, while also effective, resulted in only a 30% yield increase. The data highlight the potential economic benefits of using EPF over chemical alternatives, reinforcing the value of integrating these biocontrol agents into pest management strategies.

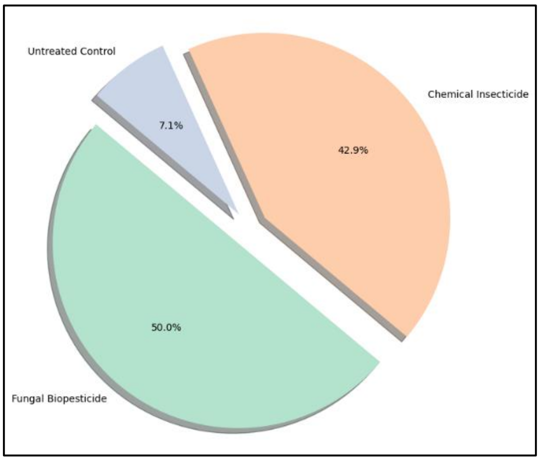

Figure 5. Graphical Analysis of Efficacy of *Metarhizium anisopliae* on Tomato Borer (*Helicoverpa armigera*)

While the results highlight the promising potential of EPF in pest management, several challenges and considerations must be addressed for successful implementation. Environmental factors, such as temperature, humidity, and UV radiation, can significantly affect the viability and efficacy of fungal applications. For instance, high temperatures may hinder fungal growth and spore viability, while excessive UV exposure can rapidly degrade conidia, reducing their infectivity as shown in above Figure 5. Therefore, optimal application timing and conditions are crucial for maximizing the effectiveness of EPF.

Environmental Factor	**Temperature (°C)**	**Humidity (%)**	**Mortality Rate (%) for *B. bassiana***	**Mortality Rate (%) for *M. anisopliae***
Optimal Conditions	25	75	85%	80%
Suboptimal Conditions	30	60	60%	55%
High UV Exposure	20	50	40%	45%

Table 4. Comparison of Environmental Factors on EPF Efficacy

In this table 4, examines the impact of various environmental factors on the efficacy of *Beauveria bassiana* and *Metarhizium anisopliae*. Optimal conditions of 25°C and 75% humidity resulted in the highest mortality rates for both fungi, demonstrating their effectiveness under ideal circumstances. As temperature increased to 30°C or UV exposure became high, mortality rates dropped significantly, indicating the sensitivity of these fungi to environmental stressors. These findings emphasize the importance of considering environmental conditions when applying EPF for pest management to maximize their effectiveness.

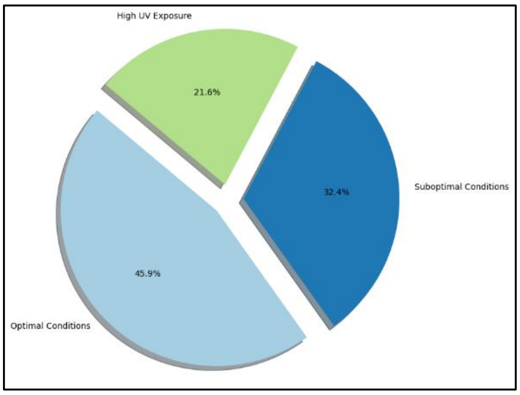

Figure 6. Graphical Analysis of Comparison of Environmental Factors on EPF Efficacy

The formulation of fungal biopesticides poses challenges that must be overcome to enhance their field efficacy. Current formulations may suffer from issues related to shelf-life and stability, necessitating ongoing research into developing more robust delivery systems. Recent advances in encapsulation technologies and formulation strategies have shown promise in improving the resilience of fungal products, suggesting pathways for future research and development as shown in above Figure 6.

Insect Species	**Feeding Reduction (%)**	**Reproductive Success Reduction (%)**	**Predation Risk Increase (%)**
Green Peach Aphid	50%	60%	40%

Tomato Borer	65%	70%	50%
Cotton Bollworm	55%	50%	45%

Table 5. Behavioral Changes in Insects Infected by EPF

In this table 5, highlights the behavioral modifications observed in insect species infected by entomopathogenic fungi. The data show that infected insects, such as green peach aphids and tomato borers, exhibit significant reductions in feeding and reproductive success, with increases in predation risk. For example, the green peach aphid experienced a 50% reduction in feeding and a 60% decrease in reproductive success. These behavioral changes can exacerbate pest population declines, further illustrating the multifaceted impact of EPF on pest dynamics in agricultural ecosystems. Understanding these behavioral effects is crucial for optimizing the use of EPF in integrated pest management.

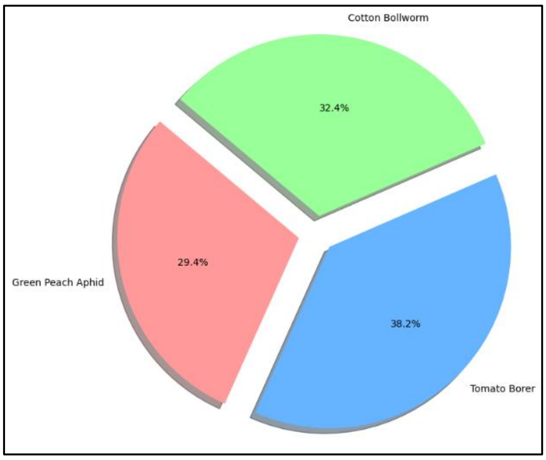

Figure 7. Graphical Analysis of Behavioral Changes in Insects Infected by EPF

Resistance development in target pest populations is another critical concern that warrants attention. Although EPF exhibit lower risks of resistance compared to chemical insecticides, the potential for pest adaptation still exists. Continuous monitoring of pest populations and the incorporation of EPF into rotation strategies with other biocontrol agents may mitigate this risk, ensuring the sustained efficacy of these biological control methods. The results of various studies demonstrate the efficacy of entomopathogenic fungi as effective biocontrol agents against agricultural pests, offering a sustainable alternative to chemical pesticides. The intricate mechanisms of infection and the ecological impacts of EPF highlight their potential role in integrated pest management strategies. However, to fully realize their benefits, ongoing research must address the challenges associated with environmental factors, formulation stability, and resistance development as shown in above Figure 7. The integration of EPF into conventional agricultural practices not only promises effective pest management but also supports broader goals of sustainable agriculture, promoting healthier ecosystems and minimizing the environmental footprint of pest control practices.

VI. Conclusion

Entomopathogenic fungi (EPF) represent a promising and sustainable alternative to chemical pesticides in agricultural pest management. The data presented in this research work underscore their efficacy in controlling key agricultural pests, such as aphids, whiteflies, and tomato borers. Through various mechanisms of pathogenicity, EPF can effectively penetrate and infect host insects, resulting in significant mortality rates and subsequent reductions in pest populations. The successful application of species like *Beauveria bassiana* and *Metarhizium anisopliae* in field trials demonstrates their potential to enhance crop yields while minimizing the ecological impact associated with traditional chemical pest control methods. The findings also highlight the importance of environmental factors in the effectiveness of EPF. Optimal conditions, including appropriate temperature and humidity levels, are crucial for maximizing their pathogenic potential. The behavioral changes induced in infected insects, such as reduced feeding and reproductive success, contribute to the overall decline of pest populations, further validating the role of EPF in integrated pest management (IPM) strategies. Despite the promising results, challenges such as environmental sensitivity, formulation stability, and the potential for pest resistance remain significant considerations. Continued research is essential to address these challenges, optimize application methods, and develop robust formulations that enhance the effectiveness of EPF in diverse agricultural contexts. Entomopathogenic fungi are a vital component of modern pest management practices. Their ability to control pest populations sustainably not only benefits agricultural productivity but also promotes ecological balance within agroecosystems. As research advances, the integration of EPF into pest management strategies holds great promise for a more sustainable and environmentally friendly approach to agriculture.

References

[1] Corbet S.A., Williams I.H., Osborne J.L. Bees and the Pollination of Crops and Wild Flowers in the European Community. Bee World. 2015;72:47–59. doi: 10.1080/0005772X.1991.11099079.

[2] Morse R.A., Calderone N.W. The value of honey bees as pollinators of US crops in 2000. Bee Cult. 2000;128:1–15.

[3] Balica G., Vostinaru O., Stefanescu C., Mogosan C., Iaru I., Cristina A., Pop C.E. Potential Role of Propolis in the Prevention and Treatment of Metabolic Diseases. Plants. 2021;10:883. doi: 10.3390/plants10050883.

[4] Nagai T., Inoue R. Preparation and the functional properties of water extract and alkaline extract of royal jelly. Food Chem. 2004;84:181–186. doi: 10.1016/S0308-8146(03)00198-5.

[5] Eteraf-Oskouei T., Najafi M. Traditional and modern uses of natural honey in human diseases: A review. Iran. J. Basic Med. Sci. 2013;16:731. doi: 10.22038/ijbms.2013.988.

[6] Neumann P., Carreck N.L. Honey bee colony losses. J. Apic. Res. 2015;49:1–6. doi: 10.3896/IBRA.1.49.1.01.

[7] Pietropaoli M., Skerl M.S., Cazier J., Riviere M.-P., Tiozzo B., Eggenhoeffner R., Gregorc A., Haefeker W., Higes M., Ribarits A., et al. BPRACTICES Project: Towards a sustainable european beekeeping. Bee World. 2020;97:66–69. doi: 10.1080/0005772X.2020.1757220.

[8] Farenhorst M., Mouatcho J.C., Kikankie C.K., Brooke B.D., Hunt R.H., Thomas M.B., Koekemoer L.L., Knols B.G.J., Coetzee M. Fungal infection counters insecticide resistance in African malaria mosquitoes. Proc. Natl. Acad. Sci. USA. 2009;106:17443–17447. doi: 10.1073/pnas.0908530106.

[9] Farenhorst M., Knols B.G.J., Thomas M.B., Howard A.F.V., Takken W., Rowland M., N'Guessan R. Synergy in efficacy of fungal entomopathogens and permethrin against west african insecticide-resistant anopheles gambiae mosquitoes. PLoS ONE. 2010;5:e12081. doi: 10.1371/journal.pone.0012081.

[10] Goblirsch M. Nosema ceranae disease of the honey bee (Apis mellifera) Apidologie. 2018;49:131–150. doi: 10.1007/s13592-017-0535-1.

[11] Dietemann V., Nazzi F., Martin S.J., Anderson D.L., Locke B., Delaplane K.S., Wauquiez Q., Tannahill C., Frey E., Ziegelmann B., et al. Standard methods for Varroa research. J. Apic. Res. 2013;52:1–54. doi: 10.3896/IBRA.1.52.1.09.

[12] Neumann P., Pettis J.S., Schäfer M.O. Quo vadis Aethina tumida? Biology and control of small hive beetles. Apidologie. 2016;47:427–466. doi: 10.1007/s13592-016-0426-x.

[13] Catão AML, Rodrigues J, Marreto RN, Mascarin GM, Fernandes ÉKK, Humber RA, Luz C (2021) Optimization of granular formulations of Metarhizium humberi microsclerotia with humectants. J Basic Microbiol 61:808–813.

[14] Días L, Pedrini N, Braga G, Ferreira P, Pupin B, Araújo C, Corrochano L, Rangel D (2020) Outcome of blue, green, red, and white light on Metarhizium robertsii during mycelial growth on conidial stress tolerance and gene expression. Fungal Biol 124:263–272.

[15] Felizatti,A, Manzano R, Rodrigues I, da Silva M, Fernandes J, Forim M (2021) Encapsulation of B. bassiana in biopolymers: improving microbiology of insect pest control. Front Microbiol 12:704812. https://doi.org/10.3389/fmicb.2021.704812

[16] Garrido-Jurado I, Fernández-Bravo M, Campos C, Quesada-Moraga E (2015) Diversity of entomopathogenic Hypocreales in soil and phylloplane of five Mediterranean cropping systems. J Invertebr Pathol 130:97–106.