Review Article

Entomopathogenic Fungi: Dual Role in Insect Control and Plant Disease Management

Abstract

Entomopathogenic fungi (EPF) are important biological agents in modern agriculture, offering eco-friendly solutions for integrated pest and disease management. With their dual functionality, EPF target a wide range of insect pests while suppressing plant pathogens, presenting a sustainable alternative to synthetic pesticides. The biology, mechanisms, and applications of EPF, highlighting their ability to parasitize insects through adhesion, enzymatic penetration, and toxin production while simultaneously managing plant pathogens via antibiosis, competition, systemic resistance induction, and direct parasitism. Advances in genomics have unveiled molecular insights into EPF pathogenicity, paving the way for biotechnological enhancements, including genetically engineered strains with improved efficacy, thermal tolerance, and host specificity. Innovative formulation technologies, such as nano-carriers and microencapsulation, have enhanced the viability and precision delivery of EPF, improving field efficacy. The integration of EPF with precision agriculture tools, including drones and sensor-based systems, allows targeted applications and data-driven pest management. Their compatibility with organic farming systems underscores their role in fostering sustainable and environmentally conscious agricultural practices. Despite these advancements, challenges remain, including environmental limitations, production costs, regulatory hurdles, and potential non-target effects. Addressing these challenges through interdisciplinary research and stakeholder education is critical for maximizing EPF's potential. As agriculture faces mounting pressures from climate change, pest resistance, and ecological degradation, EPF stand as a promising solution, contributing to soil health, biodiversity conservation, and reduced chemical dependency. The importance of EPF in shaping resilient agroecosystems, driving the transition toward sustainable agriculture while ensuring food security and environmental sustainability. The integration of cutting-edge technologies and policy support will be important in scaling the adoption of EPF-based solutions, positioning these fungi as a cornerstone in the future of agricultural innovation and sustainability.

Keywords: *Entomopathogenic, Biocontrol, Sustainability, Pathogenicity, Genomics, Formulations*

I. Introduction

Entomopathogenic Fungi (EPF)

Entomopathogenic fungi (EPF) represent a critical group of microorganisms that serve as natural regulators of insect populations (Islam *et.al.,* 2021). These fungi, encompassing genera such as *Beauveria*, *Metarhizium*, *Lecanicillium*, and *Isaria*, are found ubiquitously in terrestrial ecosystems and have evolved specialized mechanisms to infect and kill insect hosts. EPF initiate infection through adhesion to the insect cuticle, followed by penetration using hydrolytic enzymes like chitinases, proteases, and lipases. This process results in systemic invasion and eventual mortality of the insect host, making EPF important in pest population control. Beyond insect pathogenicity, EPF contribute to ecological balance by recycling nutrients from decomposed insect cadavers into the soil, promoting soil fertility and plant growth (Belousova *et.al.*, 202). Their interactions with other soil microbiota further enhance their role in maintaining soil health and suppressing plant pathogens.

Importance of Sustainable Pest and Disease Management in Agriculture

The over-reliance on synthetic chemical pesticides has posed significant challenges to agricultural sustainability. Problems such as pesticide resistance, contamination of ecosystems, and adverse effects on non-target organisms necessitate alternative approaches to pest and disease management. Sustainable pest and disease management focuses on minimizing chemical inputs while maintaining productivity and protecting biodiversity. EPF, being environmentally benign and host-specific, align perfectly with these goals (Sarkar *et.al.,* 2024). They offer a dual advantage: directly targeting insect pests and indirectly suppressing plant pathogens, thus contributing to healthier agroecosystems. Their compatibility with organic farming practices and potential for integration with other biological control agents further underscores their value in modern agriculture.

Objective of the Review: Exploring the Dual Role of EPF in Pest and Disease Control

The dual role of EPF as both entomopathogens and plant disease antagonists opens avenues for comprehensive pest and disease management strategies. On one hand, they utilize their infective properties to control insect pests, while on the other, they inhibit plant pathogens through mechanisms like mycoparasitism, antibiosis, and competition for resources. This review aims to critically examine these dual functionalities of EPF, delving into their biological mechanisms, practical applications, and contributions to sustainable agriculture. Furthermore, it will highlight recent advancements in EPF research, address challenges associated with their widespread application, and discuss future prospects (Qin *et.al.,* 2023). By doing so, this review seeks to establish EPF as a cornerstone of integrated pest and disease management systems, paving the way for eco-friendly and resilient farming practices.

II. Biology and Ecology of Entomopathogenic Fungi

Classification and Diversity of EPF

Entomopathogenic fungi (EPF) encompass a diverse group of fungi belonging to multiple taxonomic classes within the fungal kingdom. They are primarily classified under the phyla Ascomycota and Zygomycota, with notable genera including *Beauveria*, *Metarhizium*, *Isaria*, *Lecanicillium* (Ascomycota), and *Entomophthora* (Zygomycota). The diversity of EPF is reflected in their ability to infect a broad range of insect hosts, spanning over 700 insect species across various orders such as Lepidoptera, Coleoptera, Diptera, and Hemiptera. This adaptability to different hosts is facilitated by their unique infective strategies and biochemical versatility.These fungi occur naturally in soil, where they play aimportant role in regulating insect populations, and they are also found in association with plant rhizospheres, endophytically colonizing plant tissues (Hu *et.al.,* 2021).*Beauveria bassiana* and *Metarhiziumanisopliae* are among the most studied EPF due to their broad host range and commercial applicability in biocontrol.

Mechanisms of Infection in Insect Hosts

The infection process of EPF begins with the adhesion of fungal spores (conidia) to the insect cuticle. This is facilitated by hydrophobic interactions and surface proteins such as hydrophobins. Following adhesion, the fungi germinate and produce specialized structures called appressoria, which generate mechanical pressure and secrete extracellular enzymes, including chitinases, proteases, and lipases, to breach the insect’s cuticle.Once inside the host, EPF proliferate within the hemocoel, spreading through hemolymph (Butt *et.al.*, 2016). They evade the insect's immune defenses by producing immunosuppressive secondary metabolites such as destruxins in *Metarhizium* and beauvericins in *Beauveria*. These toxins disrupt cellular signaling, inhibit phagocytosis, and induce apoptosis, eventually killing the host. The fungi then emerge from the cadaver, producing conidia that are dispersed into the environment, completing their infection cycle.

Life Cycle and Environmental Adaptability

EPF exhibit a heterotrophic life cycle with distinct phases tailored to environmental conditions and host availability. The cycle includes spore germination, appressorium formation, host colonization, reproduction, and spore dissemination. EPF can survive in the absence of hosts by forming resilient conidia or dormant structures like chlamydospores, which allow them to withstand adverse environmental conditions such as extreme temperatures, UV radiation, and desiccation (Sarkar *et.al.*, 2024).Adaptability is further enhanced by their ability to colonize non-host substrates, including plant roots and organic matter in soil. This versatility not only ensures their survival but also promotes ecological interactions with other microorganisms, such as mycorrhizae and plant growth-promoting rhizobacteria.

Role of EPF in the Ecosystem

EPF play multiple ecological roles beyond their function as insect pathogens. They act as natural regulators of insect populations, contributing to the suppression of pest outbreaks and maintaining ecological balance. As soil-dwelling organisms, EPF enhance nutrient cycling by decomposing insect cadavers, releasing nitrogen and other nutrients back into the soil, which benefits plant growth (Sharma *et.al.*, 2019).EPF exhibit antagonistic interactions with plant pathogens, such as fungi and nematodes, through mechanisms including antibiosis, competition for nutrients, and production of antifungal compounds. Their colonization of plant roots as endophytes improves plant resilience to biotic and abiotic stresses, fostering a healthier agroecosystem.

III. EPF in Insect Pest Management

History and Early Applications

The use of entomopathogenic fungi (EPF) in insect pest management dates back to the late 19th century when early observations noted fungal infections in insect populations during outbreaks. The white muscardine disease caused by *Beauveria bassiana* in silkworms, marking the initial recognition of EPF as potential biocontrol agents. By the early 20th century, researchers began isolating and culturing EPF for experimental pest control. One of the earliest commercial applications was the use of *Metarhizium anisopliae* against sugarcane pests in Java in the 1930s (Murphy *et.al.,* 1990).Advances in microbial production and formulation technologies during the latter half of the 20th century spurred the development of EPF-based biopesticides. The introduction of *Beauveria bassiana* as a commercial biopesticide in the 1980s expanded the use of EPF to control pests in various crops, including cotton, vegetables, and fruit orchards. These early applications laid the groundwork for the integration of EPF into modern integrated pest management (IPM) systems.

Modes of Action Against Insect Pests

Attachment and Germination on Insect Cuticles

EPF initiate infection by attaching to the hydrophobic insect cuticle using adhesive structures and proteins, such ashydrophobins and adhesions (Table 1) (Sharma *et.al.*, 2021). This adhesion is a critical step, enabling fungal spores (conidia) to remain on the host despite environmental challenges like wind or rain. Once attached, the conidia germinate, forming germ tubes that penetrate the cuticle surface.

Penetration and Proliferation Within Insect Bodies

Penetration of the insect cuticle is achieved through a combination of mechanical pressure and enzymatic degradation. Enzymes such as chitinases, proteases, and lipases break down the insect's structural barriers, allowing the fungus to breach the exoskeleton. After penetration, EPF proliferate in the hemocoel, spreading through the hemolymph. This systemic colonization disrupts vital physiological functions, leading to the insect's death.

Production of Toxins and Enzymes

EPF produce a range of secondary metabolites, including destruxins (*Metarhiziumanisopliae*), beauvericins (*Beauveria bassiana*), and bassianolides, which exhibit insecticidal properties. These compounds impair cellular processes, disrupt immune responses, and contribute to the rapid collapse of the insect host (Krautz *et.al.*, 2014). Toxin production enhances the efficacy of infection, particularly in insects with robust immune defenses.

Table:1 Modes of Action Against Insect Pests for Entomopathogenic Fungi (EPF)(Sources: Sharma *et.al.*, 2021, Krautz *et.al.*, 2014).

Mode of Action	Description	Key Processes Involved
Adhesion to Cuticle	EPF spores adhere to the insect's exoskeleton using hydrophobic and proteinaceous interactions.	Adhesion proteins and hydrophobic surfaces enhance binding to the insect cuticle.
Germination and Penetration	Spores germinate and produce appressoria to mechanically and enzymatically breach the cuticle.	Secretion of enzymes like proteases, chitinases, and lipases facilitates cuticle degradation.
Proliferation Inside Host	Fungal hyphae invade the insect hemocoel, disrupting physiological processes.	Nutrient acquisition, hyphal spread, and secretion of toxins occur within the hemolymph.
Toxin Production	EPF produce secondary metabolites that impair host immunity and disrupt cellular functions.	Toxins such as destruxins (*Metarhizium spp.*) and beauvericin (*Beauveria spp.*).
Nutrient Deprivation	Fungi deplete nutrients essential for the insect's survival and reproduction.	Hyphal growth within host tissues deprives the insect of vital resources.
Immune Suppression	EPF modulate or suppress the insect immune response, allowing	Subversion of hemocyte responses and inhibition of

	successful colonization.	melanization pathways.
Death and Sporulation	The insect dies from systemic fungal infection, and new spores are produced on the cadaver.	Post-mortem sporulation enables dissemination of the fungus to new hosts.

Formulations and Delivery Mechanisms for Field Applications

The commercial success of EPF as biopesticides depends on effective formulations and delivery systems. Formulations include wettable powders, granules, and oil-based suspensions that enhance shelf life, stability, and ease of application (Hazra *et.al.,* 2019). Innovations in microencapsulation and nanoparticle formulations have improved the protection of fungal spores against environmental stressors such as UV radiation and desiccation.Field application methods include foliar sprays, soil treatments, and seed coatings. Foliar sprays target above-ground pests, while soil treatments and seed coatings address root-feeding pests and establish fungal colonies in the rhizosphere. Advances in drone technology and precision agriculture tools have further optimized the delivery of EPF, enabling targeted applications and reduced environmental impact (Shaari *et.al*., 2024).

IV. EPF in Plant Disease Management

Mechanisms of Action Against Plant Pathogens

Entomopathogenic fungi (EPF) exhibit multiple mechanisms in managing plant diseases, making them essential components of sustainable agricultural practices. Antibiosis and competition are among the primary methods through which EPF suppress plant pathogens. These fungi produce various secondary metabolites and antimicrobial compounds, such as destruxins from *Metarhiziumanisopliae* and bassianolides from *Beauveria bassiana,* which disrupt the cellular integrity and metabolic pathways of pathogenic fungi. EPF compete with pathogens for nutrients and colonization sites in the rhizosphere. This competition effectively limits the establishment and spread of pathogens, creating a hostile environment for their proliferation.Induction of systemic resistance in plants is another vital mechanism utilized by EPF. By colonizing plant tissues as endophytes, these fungi activate the plant's hormonal defense pathways, particularly those regulated by jasmonic acid (JA) and salicylic acid (SA) (Chen *et.al.,* 2020). This activation leads to the production of defensive enzymes such as peroxidases and polyphenol oxidases, strengthening the plant's immune system. *Beauveria bassiana* has been reported to significantly reduce disease severity in tomatoes affected by *Botrytis cinerea*, demonstrating the ability of EPF to prime plant defenses effectively.Direct parasitism of fungal pathogens is a more aggressive approach employed by EPF in disease management. The fungi secrete lytic enzymes, including chitinases and glucanases, which break down the cell walls of pathogenic fungi. For example, *Metarhizium anisopliae* has shown efficacy in targeting pathogens like *Rhizoctoniasolani* and *Sclerotiniasclerotiorum,* reducing the impact of root and stem diseases in crops. This direct attack not only eliminates pathogens but also creates a microbiological balance that supports overall plant health (Heydari *et.al.,* 2010).

Examples of EPF with Dual Functions

Certain EPF, such as *Trichoderma spp.* and *Lecanicillium spp.,* exhibit dual roles by managing both insect pests and plant diseases. *Trichoderma spp*., traditionally known for their role in plant disease control, also exhibit entomopathogenic properties. These fungi suppress pathogens like *Fusarium oxysporum* and *Pythium spp.* through antibiosis and direct parasitism while simultaneously controlling soil-dwelling pests such as nematodes. Similarly, *Lecanicilliumlecanii* effectively manages greenhouse pests like aphids and whiteflies and inhibits plant pathogens such as *Powdery Mildew*, showcasing its versatility as a biocontrol agent.

Interaction of EPF with Other Soil Microbes

The interactions between EPF and other soil microorganisms significantly enhance their efficacy in plant disease management (Islam *et.al.,* 2021). EPF often form synergistic relationships with plant growth-promoting rhizobacteria (PGPR) such as *Bacillus subtilis*, which improves root colonization, nutrient uptake, and disease resistance. Furthermore, EPF like *Beauveria bassiana* are compatible with arbuscular mycorrhizal fungi (AMF), which aid in nutrient acquisition and stress tolerance. This compatibility strengthens plant health and reduces pathogen pressure. EPF also exhibit antagonistic interactions with soilborne pathogens like *Verticillium dahliae* and *Phytophthora spp*., suppressing their growth and promoting a balanced microbial community in the rhizosphere. These interactions underline the potential of EPF as integral components of integrated disease management systems in sustainable agriculture (Bamisile*et.al.,* 2021).

V. Synergistic Role in Integrated Pest and Disease Management (IPDM)

Entomopathogenic fungi (EPF) have emerged as indispensable components of integrated pest and disease management (IPDM) strategies, owing to their compatibility with a wide range of biological, chemical, and cultural approaches (Table 2). Their dual role in targeting insect pests and suppressing plant pathogens makes them ideal for reducing reliance on synthetic chemicals and fostering sustainable agricultural practices.

Compatibility of EPF with Other Biological Control Agents

EPF exhibit significant compatibility with other biological control agents, including parasitoids, predators, and microbial antagonists (Butt *et.al.,* 2016). Studies have demonstrated that EPF can coexist and complement the action of natural enemies without causing negative interactions. *Beauveria bassiana* has been used alongside parasitoids like *Aphidiuscolemani* for aphid control in greenhouse settings. The combined application resulted in enhanced pest suppression without compromising the efficacy of the parasitoid. Similarly, the use of EPF with predators like lady beetles (*Coccinellidae*) has shown synergistic effects, as the fungal infections weaken pest populations, making them more susceptible to predation.EPF integrate effectively with microbial antagonists such as *Trichoderma spp.* and *Bacillus subtilis,* which target plant pathogens. This synergy improves overall plant health by simultaneously suppressing soilborne pathogens and insect pests, highlighting the versatility of EPF in IPDM systems.

Integration with Chemical and Cultural Pest Management Strategies

The integration of EPF with chemical and cultural pest management practices has proven to be a sustainable alternative to conventional methods (Sharma *et.al.,* 2023). EPF are compatible with several reduced-risk pesticides, allowing for combined applications that minimize environmental impact. Oil-based formulations of *Metarhizium anisopliae* have been successfully used alongside insect growth regulators (IGRs) to control locusts and grasshoppers, achieving higher efficacy than either treatment alone. These fungi are resilient to many modern fungicides when applied at recommended doses, ensuring their coexistence in mixed strategies.Cultural practices, such as crop rotation, intercropping, and cover cropping, further enhance the effectiveness of EPF in IPDM. These practices improve soil structure, moisture retention, and microbial diversity, creating a conducive environment for EPF proliferation (Hokkanen *et.al.,* 2024). For example, incorporating cover crops like clover has been shown to increase the density of *Beauveria bassiana* in the rhizosphere, improving pest suppression and reducing pathogen incidence.

Case Studies Highlighting Dual Benefits in Crop Protection

Numerous case studies illustrate the dual benefits of EPF in crop protection. In cotton fields, *Beauveria bassiana* has been applied to manage whiteflies while simultaneously suppressing root rot caused by *Rhizoctoniasolani*. Field trials reported a 70% reduction in whitefly populations and a 50% decrease in root rot incidence, demonstrating the fungi's ability to address both insect and pathogen challenges.Another example is the use of *Metarhizium anisopliae* in sugarcane to control termites and reduce damage from soilborne pathogens like *Pythium spp.*. The dual application resulted in increased crop yield and improved root health, validating the efficacy of EPF in addressing multiple threats simultaneously (Angon *et.al.,* 2023).In tomato cultivation, the combination of *Beauveria bassiana* with plant growth-promoting rhizobacteria (*Bacillus subtilis*) was found to enhance plant resistance to *Botrytis cinerea* and aphid infestations. This integrated approach led to a 40% increase in yield compared to conventional pesticide treatments, underscoring the economic and ecological benefits of EPF-based IPDM strategies.These examples illustrate the potential of EPF to provide sustainable solutions for pest and disease management, reducing chemical inputs, enhancing crop health, and improving agricultural productivity. By integrating EPF with biological, chemical, and cultural practices, IPDM systems can achieve greater resilience and effectiveness, contributing to the long-term sustainability of agriculture (Kalbande*et.al.,* 2021).

Table:2 Synergistic Role of Entomopathogenic Fungi in Integrated Pest and Disease Management (IPDM) (Source: Butt *et.al*., 2016, Sharma *et. al*., 2023).

Aspect	Description	Examples/Key Contributions
Biological Control Agents	EPF act as natural antagonists to insect pests, reducing reliance on chemical pesticides.	*Beauveria bassiana* for whitefly and aphid management.
Compatibility with IPM Practices	EPF can be combined with cultural, mechanical, and biological pest control strategies for enhanced effectiveness.	Integration with pheromone traps or crop rotation to reduce pest populations sustainably.
Dual Role in Pathogen Control	Some EPF also exhibit antagonistic activity against plant pathogens, enhancing disease management.	*Metarhizium spp.* and *Trichoderma spp.* for managing root pathogens like *Rhizoctonia*.
Reduced Pesticide Dependence	Combining EPF with reduced doses of chemical pesticides leads	Synergy between *Beauveria bassiana* and neonicotinoids for

	to synergistic effects and minimizes resistance.	controlling aphids.
Sustainability	EPF enhance ecological balance by targeting pests without harming beneficial organisms.	Protection of pollinators and soil microflora when EPF are used instead of broad-spectrum insecticides.
Compatibility with Biopesticides	EPF can work synergistically with other microbial agents like *Bacillus thuringiensis* for broader pest control.	Combined use of *Metarhizium* and *Bt* for caterpillar and beetle infestations.
Environmental Safety	EPF are eco-friendly, reducing chemical residues and promoting long-term pest and disease management.	Application in organic farming systems to align with sustainable agriculture principles.
Innovative Formulations	Development of formulations combining EPF with botanical extracts or nanomaterials for enhanced efficacy.	Nano-formulated *Beauveria bassiana* for extended shelf-life and effective pest management.
Enhanced Soil Health	EPF improve soil microbial diversity while controlling soil-borne insect pests and pathogens.	*Metarhizium anisopliae* for controlling root grubs and improving soil organic matter content.

VI. Advances in EPF Research and Applications

Genomic and Molecular Insights into EPF Mechanisms

The advancement of genomic and molecular biology tools has significantly enhanced our understanding of the biology and mechanisms of entomopathogenic fungi (EPF). Genome sequencing of key EPF species such as *Metarhizium anisopliae* and *Beauveria bassiana* has revealed genes encoding pathogenicity factors, including hydrolases, toxin biosynthesis pathways, and regulators of host-specificity. For example, destruxin biosynthesis pathways in *Metarhizium* have been elucidated, identifying genes critical for toxin production and virulence. Transcriptomic analyses further highlight the dynamic expression of genes during host infection, shedding light on how EPF adapt to different stages of infection (Samal *et.al.,* 2023).Molecular studies have also uncovered signaling pathways involved in spore adhesion, cuticle penetration, and immune evasion in insects. The MAPK and cAMP signaling pathways play essential roles in fungal development and pathogenicity. The identification of these molecular networks has provided targets for genetic manipulation to enhance the efficiency and specificity of EPF.

Innovative Formulation Technologies for Improved Field Efficacy

The success of EPF as biocontrol agents depends heavily on their formulation for field application (Mantzoukas*et.al.,* 2020). Recent advances in formulation technologies have significantly improved the stability, shelf life, and delivery of EPF under diverse environmental conditions. Oil-based formulations have gained popularity due to their ability to protect fungal spores from desiccation and UV radiation, enhancing field performance. Encapsulation techniques using polymers and hydrogels have been developed to provide controlled release and improved adherence to plant surfaces.The use of nanotechnology has further revolutionized EPF formulations. Nano-carriers and microencapsulation systems enable precise delivery of fungal spores to target sites, reducing wastage and enhancing efficacy. These advanced formulations also facilitate the combination of EPF with other agrochemicals, ensuring compatibility and promoting integrated pest management (Behl *et.al.,* 2024).

Biotechnological Modifications to Enhance EPF Performance

Biotechnology has opened new avenues for improving the performance of EPF through genetic engineering and strain selection. Genetic modifications have been employed to overexpress genes involved in toxin production and enzyme activity, increasing the virulence of EPF against specific insect pests. For example, overexpression of chitinase genes in *Beauveria bassiana* has enhanced its ability to degrade insect cuticles, improving infection rates. Gene editing technologies like CRISPR-Cas9 have facilitated precise manipulation of EPF genomes to enhance their adaptability to adverse environmental conditions (Mahmood *et.al.,* 2023). Efforts to create hybrid strains with enhanced thermal tolerance, UV resistance, and compatibility with other biological control agents are underway, promising to expand the applicability of EPF in diverse agroecosystems.

Role of EPF in Addressing Climate Change Challenges in Agriculture

Climate change poses significant challenges to agricultural systems, including increased pest outbreaks and altered pathogen dynamics. EPF offer a sustainable solution to these challenges by providing eco-friendly pest and disease control. As climate change alters pest distributions, EPF can be adapted to target emerging threats through strain selection and biotechnological modifications.EPF contribute to soil health and carbon sequestration by decomposing insect cadavers and releasing organic matter into the soil. This function aligns with the goals of sustainable agriculture, mitigating the effects of climate change by enhancing soil fertility and resilience. Recent research also highlights the potential of EPF to interact positively with heat- and drought-tolerant crops, enabling plants to cope with abiotic stress.The integration of EPF into climate-smart agricultural practices represents a promising strategy for addressing the dual challenges of pest management and environmental sustainability (Zanzana*et.al.,* 2024). By leveraging advances in genomic insights, formulation technologies, and biotechnological innovations, EPF can be positioned as key tools in combating the impacts of climate change on agriculture.

VII. Limitations and Challenges in EPF Utilization

Entomopathogenic fungi (EPF) have demonstrated immense potential as biocontrol agents for integrated pest and disease management. Their large-scale utilization faces several limitations and challenges that need to be addressed to maximize their efficacy and adoption. These challenges stem from environmental, economic, regulatory, and ecological factors that influence their performance and acceptance.

Environmental and Climatic Factors Affecting EPF Efficacy

EPF are highly sensitive to environmental conditions, which significantly impact their effectiveness in the field. Temperature, humidity, and UV radiation are critical factors that determine the survival, germination, and infection potential of fungal spores. High temperatures, particularly above 30°C, can reduce the virulence of many EPF species, such as *Beauveria bassiana* and *Metarhiziumanisopliae*. Conversely, prolonged exposure to low temperatures slows down fungal growth, affecting their ability to infect target insects.Humidity is another essential factor, as EPF require moist conditions for spore germination and host infection (Islam *et.al.*, 2021). In arid regions, low humidity often hampers the efficacy of EPF applications. Furthermore, UV radiation can damage fungal spores, reducing their viability and persistence in the field. Studies show that unprotected spores of *Beauveria bassiana* lose more than 50% viability after two hours of direct sunlight exposure. These environmental dependencies limit the broader applicability of EPF, particularly in regions with extreme or variable climates.

Challenges in Large-Scale Production and Commercialization

The large-scale production of EPF poses significant technical and economic challenges. Mass production of high-quality fungal spores requires specialized facilities and substrates, which can be costly. Solid-state fermentation, commonly used for EPF production, is labor-intensive and yields variable results. Liquid fermentation, while scalable, often requires expensive nutrient media, increasing production costs (Formenti*et.al.*, 2014).Ensuring the long-term stability of EPF products during storage and transportation further complicates commercialization. Fungal spores are sensitive to desiccation and temperature fluctuations, necessitating advanced formulations that protect spore viability. Maintaining genetic consistency and avoiding contamination during production are critical, as variations in fungal strains can lead to inconsistent field performance. These production bottlenecks limit the availability of affordable EPF products for farmers.

Regulatory Hurdles and Public Acceptance

The registration and approval of EPF as biopesticides involve complex regulatory processes that vary by country. Regulatory agencies often require extensive data on the efficacy, safety, and environmental impact of EPF products, leading to time-consuming and expensive approval procedures. For example, in the United States, the Environmental Protection Agency (EPA) mandates rigorous testing to ensure that EPF do not pose risks to non-target organisms or ecosystems (Etterson*et.al.*, 2017).Public acceptance of EPF-based products also remains a challenge. Despite being a natural alternative to chemical pesticides, there is limited awareness among farmers and consumers about the benefits of EPF. Concerns over potential risks to beneficial insects, such as pollinators, further hinder their adoption. Educating stakeholders and promoting the ecological benefits of EPF are necessary to overcome these barriers.

Risks of Non-Target Effects and Ecosystem Disruption

EPF are generally regarded as safe for non-target organisms, but concerns about unintended ecological consequences persist. Some EPF species have broad host ranges, which may inadvertently affect non-target insects, including pollinators, decomposers, and other beneficial arthropods. Laboratory studies have shown that high concentrations of *Metarhizium anisopliae* can affect the foraging behavior of honeybees, though field-level impacts are minimal.The introduction of EPF into non-native ecosystems also raises concerns about potential disruptions to local microbial communities. EPF may outcompete native fungal species or alter soil microbial diversity, with unforeseen consequences for ecosystem balance. Addressing these risks requires comprehensive environmental impact assessments and the development of species-specific formulations to minimize non-target effects (Devos *et.al.,* 2019). Efforts to mitigate these limitations include genetic improvements to enhance EPF tolerance to environmental stressors, innovative formulations to improve spore stability, and targeted education and outreach to increase public and regulatory acceptance. By addressing these challenges, the potential of EPF as sustainable biocontrol agents can be fully realized, contributing to environmentally friendly pest and disease management.

VIII. Future

The future of entomopathogenic fungi (EPF) in pest and disease management lies in the development of innovative strategies to overcome current limitations and enhance their applicability. Advances in biological research, formulation technologies, and agricultural practices offer new avenues to maximize the potential of EPF as sustainable biocontrol agents.

Exploration of Novel EPF Species and Strains

One promising area of research is the discovery and characterization of novel EPF species and strains with unique properties. Advances in metagenomics and environmental sampling techniques have facilitated the identification of previously unrecognized fungal species from diverse ecosystems, including arid regions, forests, and extreme habitats (Ejaz *et.al.,* 2024). These novel strains often exhibit greater adaptability to specific environmental conditions, such as high temperatures or low humidity, making them suitable for use in challenging agroecosystems. Newly identified strains of *Metarhizium* and *Beauveria* have demonstrated enhanced virulence and environmental resilience. Efforts to bioprospect EPF from endemic regions can also yield strains with specialized host specificity, minimizing the risk to non-target organisms. Furthermore, the application of genome editing tools like CRISPR-Cas9 enables the development of engineered strains with improved efficacy, faster infection cycles, and broader host compatibility (Bisht *et.al.,* 2019).

Advancements in Delivery Systems for Precise Applications

The development of advanced delivery systems is critical to improving the field efficacy of EPF. Precision delivery technologies, such as microencapsulation and nanotechnology, have emerged as transformative tools for ensuring the targeted application of fungal spores. Microencapsulation techniques, for example, provide a protective coating around fungal spores, shielding them from environmental stressors like UV radiation and desiccation, while enabling controlled release upon contact with insect hosts (Saminathan*et.al.,* 2025).The use of drones and unmanned aerial systems (UAS) for EPF dispersal has gained attention in precision agriculture. These systems enable the precise application of fungal biopesticides to specific crop zones or pest hotspots, reducing wastage and optimizing coverage. Automated irrigation systems can be adapted to deliver EPF-based products directly to the rhizosphere, enhancing soil-dwelling pest control.

Integration with Precision Agriculture and Digital Tools

The integration of EPF with precision agriculture technologies and digital tools offers new possibilities for optimizing pest and disease management. Data-driven approaches, including remote sensing, geographic information systems (GIS), and machine learning, can monitor pest populations, predict outbreaks, and guide the application of EPF at the right time and location.For example, real-time pest monitoring systems using pheromone traps equipped with sensors can identify pest thresholds, triggering the release of EPF-based biopesticides through automated systems. Furthermore, mobile apps and decision-support tools can provide farmers with tailored recommendations for EPF use based on local pest pressures and environmental conditions, increasing adoption and efficacy.

Potential Role in Organic and Sustainable Farming Systems

EPF are particularly well-suited for integration into organic and sustainable farming systems due to their natural origin and minimal environmental impact (Nardone *et.al.,* 2004). Unlike chemical pesticides, EPF pose negligible risks to soil health, water quality, and non-target organisms, aligning with the principles of organic agriculture. Their ability to colonize plant roots as endophytes further enhances plant health by improving resistance to both pests and pathogens.As consumer demand for organic produce continues to grow, the adoption of EPF in organic farming systems is expected to increase. Efforts to certify EPF products for organic use and develop formulations compatible with organic standards are underway, facilitating their broader acceptance. EPF can be combined with other sustainable practices, such as intercropping and cover cropping, to create resilient agroecosystems that reduce chemical inputs and enhance biodiversity (Ndakidemi*et.al.,* 2021).These future prospects highlight the transformative potential of EPF in modern agriculture. By leveraging advancements in biological research, technology, and sustainable practices, EPF can play aimportant role in addressing global challenges such as food security, climate change, and environmental conservation. Continued investment in research and innovation will be essential to unlocking the full potential of these versatile biocontrol agents.

Conclusion

Entomopathogenic fungi (EPF) hold immense potential as sustainable agents for integrated pest and disease management, addressing critical challenges in modern agriculture. Their dual role in targeting insect pests and suppressing plant pathogens, combined with advancements in genomic insights, innovative formulations, and precision delivery systems, underscores their versatility. The exploration of novel species, biotechnological modifications, and integration with digital tools further enhances their applicability across diverse agroecosystems. Despite environmental and regulatory challenges, EPF offer eco-friendly solutions aligned with the principles of organic and sustainable farming, contributing to biodiversity preservation and reduced chemical dependency. As global demand for sustainable agriculture grows, continued research, stakeholder education, and supportive policies are essential to fully harness EPF's potential. These fungi represent a transformative step toward resilient, environmentally conscious, and economically viable agricultural practices.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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