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REVIEW ARTICLE

Diversity of entomopathogenic fungi (EPF) and their role as sustainable tools in insect pest management: A review

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Abstract

Insect pest management has been predominantly dependent on synthetic pesticides for decades. This trend persisted until the landmark publication of Rachel Carson's "Silent Spring" in 1962, which raised global concern over the environmental and health risks posed by chemical pesticides. Since then, the search for safe, eco-friendly and effective alternatives has become a global priority. Biopesticides have emerged as one of the most promising options, derived from natural sources such as microorganisms, plant extracts and beneficial insects. They have minimal environmental impact and are safe for non-target organisms and align well with integrated pest management (IPM) practices. Despite accounting for only 3–5 % of the global pesticide market, biopesticides are witnessing a rapid annual growth rate of 10–15 %, driven by increasing awareness and growing demand for residue-free agricultural produce. Among biopesticides, entomopathogenic fungi (EPF) form a distinct group known as mycoinsecticides, which infect and kill insect pests through contact. Unlike other microbial agents that require ingestion, EPF penetrate the insect cuticle, germinate and then colonise the host, making them effective against a broad range of pests. Formulated as wettable powders, emulsifiable concentrates, or granules, these mycopesticides have shown pest control efficacy between 60 % and 90 % depending on the species and environmental conditions. Additionally, certain EPF may establish endophytic relationships with specific plant species and trigger induced systemic resistance, further contributing to crop protection. However, their wider application faces constraints like slower action, environmental sensitivity and formulation challenges. Advances in biotechnology, formulation techniques and integration into IPM can help overcome these limitations and enhance their adoption in sustainable agriculture.

Keywords: biopesticides; entomopathogenic fungi; IPM; mycoinsecticides; pest management; sustainable agriculture

Introduction

Entomopathogenic fungi (EPF), a diverse group of fungi that infect and kill insects and other arthropods, act as natural enemies of many economically important insect pests and have gained significant attention as promising alternatives to chemical insecticides in integrated pest management (IPM) programs. Entomopathogenic fungi are defined as "fungi that parasitise and kill insects by invading and proliferating within their hosts, ultimately leading to death" (1). Unlike bacteria or viruses, EPFs do not require ingestion by the host; instead, they infect through direct contact with the insect cuticle, followed by germination and penetration, making them especially suitable for controlling piercing-sucking pests such as whiteflies, aphids and thrips.

The use of EPF in pest management is rooted in ecological sustainability and the growing demand for safer agricultural practices. As conventional insecticides often lead to resistance development, environmental contamination and negative effects on non-target organisms, entomopathogenic fungi offer a viable biological control strategy that aligns with global efforts to reduce reliance on synthetic chemicals. Among the most studied and commercially utilised genera are *Beauveria*, *Metarhizium*, *Isaria* and *Lecanicillium*. These fungi have demonstrated efficacy against a wide range of insect pests in both field and greenhouse conditions (2). EPF acts by adhering to the host cuticle, penetrating it using mechanical pressure and enzymatic degradation (via proteases, chitinases and lipases) and then proliferating inside the host body, releasing toxins that disrupt physiological functions and cause death. Importantly, some EPF strains are host-specific, environmentally benign and can be mass-produced using simple fermentation techniques. Advances in formulation technology, including oil-based and granular forms, have further enhanced their shelf life, efficacy and field stability (3).

With increasing concern over pesticide residues and ecological imbalance, the integration of entomopathogenic fungi into pest management programs represents a sustainable and effective approach. Continued research on fungal strain improvement, compatibility with other control agents and regulatory support will pave the way for their broader adoption in modern agriculture. Thus, entomopathogenic fungi have become central to eco-friendly pest suppression strategies in the 21st century.

Emerging trends and global market growth of biopesticides with a focus on India

Globally, the adoption of biopesticides has grown considerably, driven by environmental concerns and stricter regulations on chemical pesticide use. The European Union leads with biopesticides making up about 30 % of total pesticide usage, followed by the United States (25 %), Brazil (22 %) and the global average at 18 % (4). India, however, lags with only 12 %, highlighting the need for improved regulatory support, farmer education and extension initiatives to encourage wider adoption (Fig. 1). Despite this gap, India's biopesticide sector shows promise, with increasing diversification and product approvals. As of 2024, data from the Central Insecticides Board and Registration Committee (CIBRC) indicate that fungal-based biopesticides have the highest number of registered products in India (150), led by entomopathogenic fungi such as *Beauveria bassiana*, *Metarhizium anisopliae* and *Lecanicillium* spp. Bacterial biopesticides, primarily *Bacillus thuringiensis* Berliner, account for around 120 products, while botanicals, especially neem-based formulations, contribute 100 registrations as shown in Fig. 2 (5). Viral biopesticides, mainly nuclear polyhedrosis viruses (NPVs), are the least represented, with only 30 products, reflecting production complexities and host-specific action. This global shift reflects a broader global commitment to reducing chemical pesticide dependence and fostering environmentally sustainable agriculture. Increasing consumer demand for residue-free produce and advancements in biopesticide formulations are also propelling this growth across regions.

Classification of entomopathogenic fungi

Entomopathogenic fungi are diverse and are classified across multiple fungal phyla based on their morphological, reproductive and molecular characteristics. These fungi play a vital role in

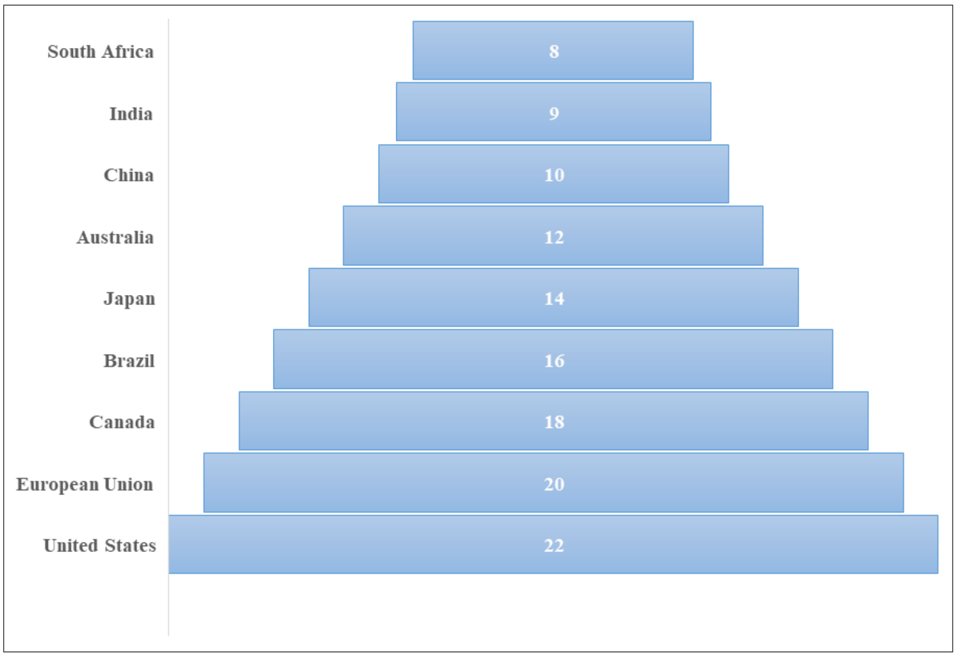

Fig. 1. Regional biopesticide share (%) in the total pesticide market, 2024 (4).

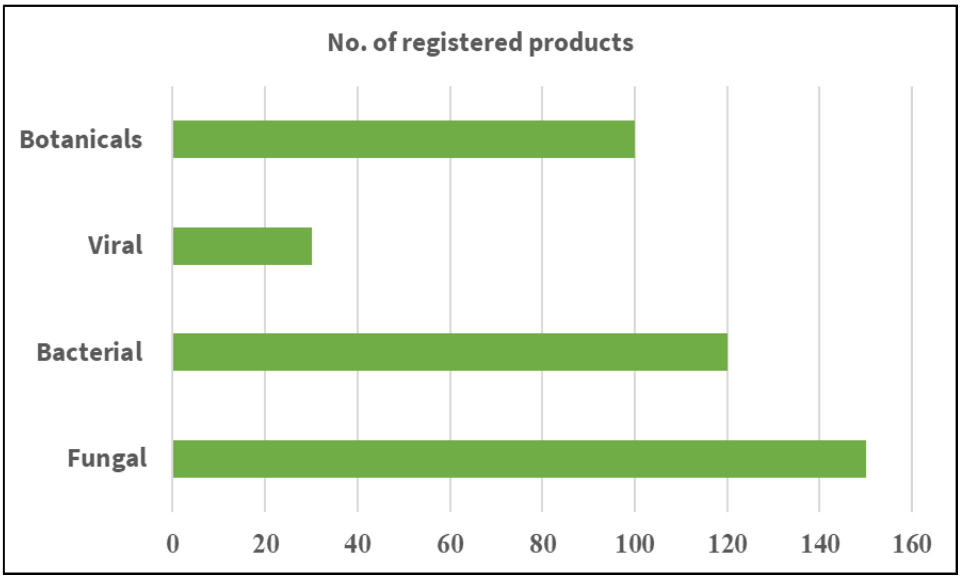

Fig. 2. Status of biopesticide registrations in India as of 2024 (5).

natural and applied biological control of insect pests.

Phylum Oomycota

Oomycetes have coenocytic hyphae with cellulose in their walls and lack chitin. They produce biflagellate zoospores and reproduce sexually via gametangial fusion between antheridia and archegonia. While most species are saprophytic or plant pathogens, some infect mosquito larvae. Lagenidium giganteum Couch is a well-studied mosquito pathogen (6). Other *Lagenidium* species infect aquatic crustaceans like crabs and *Leptolegnia* spp. also parasitise mosquito larvae and other dipterans.

Phylum Chytridiomycota

These fungi have chitinous cell walls, produce uniflagellate zoospores and typically form a thallus that can develop into coenocytic hyphae or resting spores. Phylogenetically, they are considered basal fungi. The genus *Coelomomyces* (Blastocladiales) contains over 70 known insect-pathogenic species, especially targeting Diptera and Hemiptera (7). Their thick-walled sporangia are resistant and use copepods as alternate hosts. Other chytrid fungi like *Myriophagus* (Chytridiales) and *Coelomycidium* (Blastocladiales) infect pupae of mosquitoes and blackflies.

Phylum Zygomycota

Zygomycetes typically have non-septate, multinucleate hyphae and reproduce sexually via zygospore formation through gametangial fusion. Though molecular studies show Zygomycota is not monophyletic, several species are associated with insects. *Smittium morbosum* S.W. Peterson (Trichomycetes) infects mosquito larvae, though most Trichomycetes exhibit weak or symbiotic associations (8). The order *Entomophthorales* includes over 200 obligate and facultative insect-pathogenic species. Some produce resting spores for survival and secondary spores for rapid infection cycles.

Phylum Ascomycota and Deuteromycota

Ascomycetes have septate haploid mycelia and produce eight ascospores within a sac-like ascus. They lack motile spores. Their classification is complicated by the separation of sexual (teleomorph) and asexual (anamorph) stages. *Cordyceps* is a well-known, complex genus, recently split into multiple genera, such as *Ophiocordyceps*, with several species being insect-pathogenic. *Ascosphaera apis* causes chalkbrood in honey bees through spore ingestion. Several asexual genera, such as *Beauveria*, *Metarhizium*, *Hirsutella*, *Lecanicillium*, *Paecilomyces*, *Tolypocladium*, *Culicinomyces* and *Aschersonia,* include species that have demonstrated entomopathogenicity. Many of these relationships between teleomorphs and anamorphs have been clarified through molecular studies (9).

Phylum Basidiomycota

Few basidiomycetes are entomopathogenic. Genera such as *Septobasidium* (Septobasidiales) have been reported to infect insects like scale insects. However, most of these associations are symbiotic rather than pathogenic (10).

History and evolution of entomopathogenic fungi

The history and evolution of EPF spans centuries, with foundational discoveries shaping our understanding of biological pest control. The earliest records of EPF trace back to the 1500s-1600s, when muscardine diseases were observed in silkworms in Europe. A breakthrough came in 1835, when Italian scientist Agostino Bassi identified the fungus *Beauveria bassiana* (Bals.-Criv.) Vuill. as the cause of white muscardine, marking the first scientific proof that microorganisms could cause animal disease, preceding even Pasteur's germ theory (11). In 1879, Russian scientist Élie Metchnikoff discovered green muscardine, caused by *Metarhizium anisopliae* (Metschn.) Sorokin and by the 1880s, this fungus had been used in early attempts at biological control against beetle pests in sugar beet fields.

Despite these early successes, the mid-20th century saw a decline in EPF use due to the rise of chemical pesticides. Interest resurged in the 1960s-1980s, as concerns over pesticide resistance and environmental harm grew. This period saw the isolation of new EPF species like *Culicinomyces* and advances in fungal taxonomy. The 1990s marked the commercial release of EPF-based biopesticides, including formulations of *Beauveria*, *Metarhizium* and *Lecanicillium*, while modern molecular tools in the 2000s-2010s enabled detailed phylogenetic studies, revealing multiple independent evolutions of insect-pathogenicity across fungal lineages. By the 2020s, fossil evidence from mid-Cretaceous Burmese amber confirmed that EPFs have existed for at least 99 million years, representing some of the oldest direct records of insect-parasitic fungi (12). Today, they are recognised not only for their pest-control potential but also for their roles as plant endophytes, biofertilizers and ecological partners, highlighting a significant transformation in their ecological function and scientific perception.

Mode of infection

Entomopathogenic fungi represent a critical component of biological control strategies due to their ability to infect and kill a broad range of insect pests in an environmentally sustainable manner. Unlike other microbial control agents, such as bacteria or viruses that typically require ingestion by the insect, entomopathogenic fungi invade their host through direct contact (Fig. 3). The infection process begins when the fungal spores, known as conidia, come into contact with the insect's cuticle. These conidia adhere to the host surface primarily through hydrophobic interactions and electrostatic forces. Once attached, the conidia germinate under favourable environmental conditions, particularly under conditions of high relative humidity and moderate temperatures. The germinating spores produce germ tubes or specialised infection structures called appressoria, which exert mechanical pressure on the insect cuticle and secrete a suite of cuticle-degrading enzymes (2).

These enzymes, primarily proteases (like Pr1), chitinases and lipases, play a vital role in breaching the insect's protective outer layer. Proteases degrade the protein matrix, chitinases target chitin (a key component of the exoskeleton) and lipases break down cuticular lipids. This enzymatic action allows the fungus to penetrate the exoskeleton and enter the insect’s hemocoel (body cavity), bypassing the digestive system entirely. Once inside, the fungus may exhibit a yeast-like growth phase and proliferates by forming blastospores, which circulate within the hemolymph. During this invasive phase, the fungus secretes a range of secondary metabolites and toxins that help suppress the insect's immune system, disrupt cellular functions and eventually lead to the host's death (3). Among the notable entomopathogenic fungi, *B. bassiana* and *M. anisopliae* are the most extensively studied and commercially utilised. *Beauveria bassiana* produces toxins such as beauvericin, bassianolide and tenellin. Beauvericin functions as an

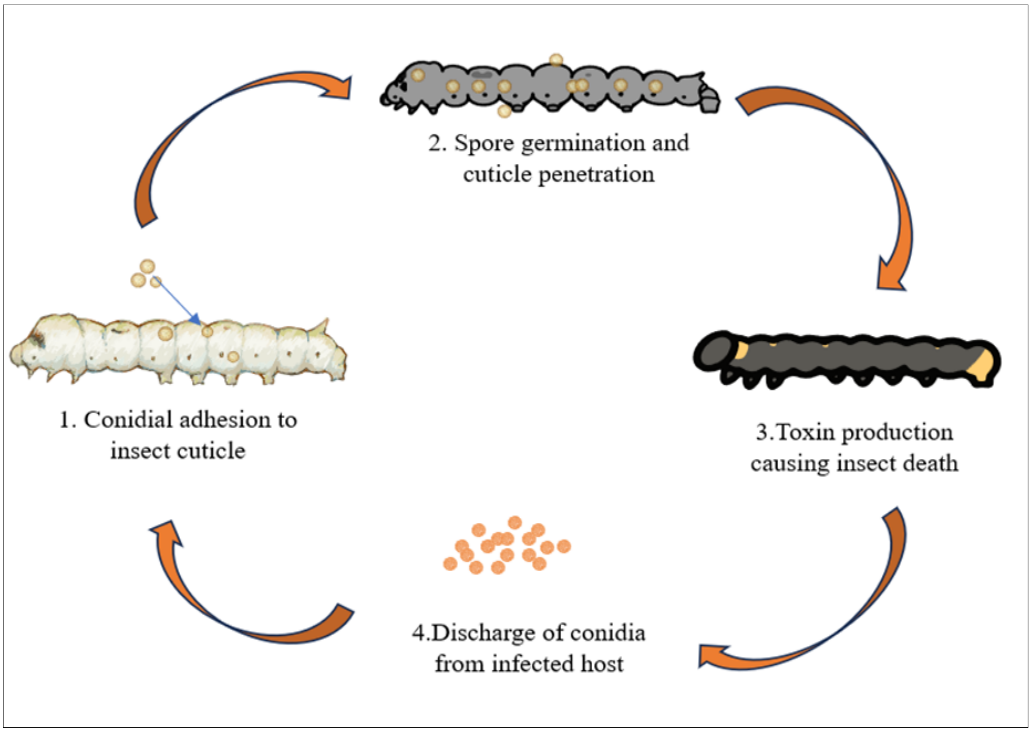

Fig. 3. Infection process of entomopathogenic fungi in insect pests.

ionophore, altering ion gradients and disrupting mitochondrial function, leading to apoptosis. Bassianolide, a cyclooligomeric depsipeptide, contributes to virulence by inducing cell lysis and paralysis. Tenellin has antimicrobial and immunosuppressive properties, further enhancing the fungus's ability to colonise the host. Similarly, *M. anisopliae* synthesises destruxins (A, B and E), which are cyclic hexadepsipeptides that interfere with calcium signalling, reduce phagocytic activity of hemocytes and impair muscle contractions, ultimately causing insect paralysis (13).

Other fungi, such as *Lecanicillium lecanii* (Zimm.) Zare & W. Gams and *Isaria fumosorosea* (Wize) Brown & Smith , also produce unique metabolites. *Lecanicillium lecanii* produces compounds like vertilecanin and dipicolinic acid, which suppress hemocyte activity and contribute to immunosuppression. *Isaria fumosorosea* synthesises cycloaspeptides and beauvericin-like compounds that have neurotoxic and cytotoxic effects. These metabolites not only help in overcoming the host's immune defence but also speed up host mortality, enhancing the efficacy of the fungal infection. Upon the death of the insect, which generally occurs within 3 to 10 days, depending on the fungal species and host susceptibility, the fungus resumes its mycelial growth, eventually breaching the insect cuticle outwardly. Under optimal humidity and temperature, the fungus sporulates on the cadaver, producing new conidia that are released into the environment to initiate further infections. This natural recycling of fungal spores supports the spread of the pathogen and establishment of epizootics in pest populations.

Fungi as insect pathogens

In recent years, there has been a growing resurgence of interest in fungi that naturally infect and kill insects, primarily due to their ecological safety and potential as powerful biological control agents. These insect-pathogenic fungi, known as entomopathogenic fungi, have been the focus of numerous studies aiming to find sustainable alternatives to synthetic pesticides. Research has revealed that over 750 fungal species, predominantly from the hyphomycetes (such as *Beauveria* and *Metarhizium*) and entomophthorales (like *Entomophthora*), are capable of causing fatal infections in insects (2). Their mechanisms involve penetrating the insect cuticle, proliferating within the host and eventually leading to host death, often releasing spores to infect new hosts. At least 171 commercial mycoinsecticide products have been developed globally using around 12 potent fungal species. These include well-known species, such as *B. bassiana*, *M. anisopliae*, *B. brongniartii* and *Lecanicillium* spp. (formerly *Verticillium lecanii*), *Hirsutella thompsonii* Fisher, *Cladosporium oxysporum* Berk. & M.A. Curtis and *I. fumosorosea* (previously *Paecilomyces fumosoroseus*), which are being formulated and applied across various crops. These fungi are effective against pests from multiple insect orders, including Hemiptera (aphids, whiteflies), Diptera (flies), Coleoptera (beetles), Lepidoptera (caterpillars), Orthoptera (grasshoppers) and Hymenoptera (wasps, bees) (14).

In most cases, the larval and nymphal stages are more susceptible due to their softer cuticles, although in some pests the adult stage can be equally vulnerable. Some fungi demonstrate high host specificity, like *Aschersonia aleyrodis* Webber , which infects only whiteflies and *Nomuraea rileyi* (Farlow) Samson, which targets lepidopteran larvae, making them ideal for selective pest control. On the other hand, fungi like *B. bassiana* and *M. anisopliae* have an exceptionally wide host range, reportedly affecting over 700 insect species. This versatility makes them suitable candidates for broad-spectrum pest management across multiple cropping systems (Table 1). Their adaptability to various application methods, including foliar sprays and soil treatments, further enhances their practical utility in diverse agroecological zones. Despite considerable success against soft-bodied insects like aphids, thrips and whiteflies, research into fungal biocontrol of hard-bodied pests like scarab beetles in sugarcane and maize borers is also emerging. This growing body of research underscores the vast and still underutilised potential of EPF, suggesting that many more effective strains may be discovered and harnessed in the future to provide environmentally friendly and targeted pest control solutions.

Table 1. EPF are used against various insect pests on crops

Fungal species	Strains	Target insect pests	Host crops	References
Paecilomyces fumosoroseus	n 32	*Plutella xylostella*	Cabbage, Canola	(15)
Beauveria bassiana	-	*Bemisia tabaci*	Melon	(15)
Nomuraea rileyi	-	*Spodoptera litura*	Soybean, Groundnut	(15)
Metarhizium anisopliae	PDRL526, PDRL711	*Lipaphis erysimi*	Canola (*Brassica napus* L.)	(15)
Beauveria bassiana	PDRL1187	*Aphis craccivora*	Canola, Mustard	(15)
Verticillium lecanii	PDRL922	*Myzus persicae*	Cabbage, Canola	(15)
Paecilomyces lilacinus	PDRL812	*Lipaphis erysimi*	Canola	(15)
Hirsutella thompsonii	-	*Aphis craccivora*	Cowpea	(16)
Cladosporium oxysporum	-	*Aphis craccivora*	Cowpea	(16)
Verticillium lecanii	-	*Myzus persicae*	Chili	(17)

Entomopathogenic fungi as endophytes

EPF are naturally occurring microorganisms that infect and kill insects and many can also live harmlessly within plant tissues as endophytes. As endophytes, they establish mutualistic associations that enhance plant health, strengthen defence mechanisms and indirectly suppress insect pests. This dual functionality provides an eco-friendly strategy for pest management by combining direct insecticidal activity with plant-mediated resistance (1, 2). For instance, *M. anisopliae* colonising cotton reduced oviposition and larval survival of *Helicoverpa armigera* (Hübner) , while *B. bassiana* in mustard effectively suppressed populations of *Lipaphis erysimi* (Kaltenbach) (2, 15). Similarly, *Lecanicillium longisporum* (Zimm.) Zare & W. Gams in cucumber simultaneously controlled *Aphis gossypii* Glover and powdery mildew, demonstrating its dual biocontrol potential (3). These examples highlight the importance of EPF in sustainable agriculture, bridging plant-microbe-insect interactions for effective biological control (Table 2).

Mycoinsecticides

The application of microbial control agents, especially EPF, has been extensively explored for managing a variety of pests affecting both orchard and field crops. Numerous fungal species have shown promising insecticidal activity and have been developed into commercial products targeting pests of significant economic importance. The utilisation of mycoinsecticides, particularly in vegetable pest management, has been documented in many countries worldwide. These fungi offer an environmentally sustainable alternative to chemical insecticides and are often compatible with (IPM) strategies. Advances in formulation technologies have improved their shelf life, application ease and field persistence. However, while several EPF demonstrate high virulence against lepidopteran pests under laboratory conditions, their performance in the field is often inconsistent. This variability in field efficacy is largely influenced by environmental factors, notably temperature and humidity.

Recent studies emphasise the need for selecting or engineering fungal strains with enhanced thermotolerance and UV-B resistance to improve their efficacy in open-field conditions (18). A follow-up investigation further highlighted that Metarhizium isolates from Brazil showed significant variation in temperature-dependent activity and UV-B tolerance, reinforcing the importance of local strain adaptability in tropical and subtropical IPM (19). These findings suggest that geographic origin and climatic adaptation are crucial factors in strain selection for effective biocontrol. Further integration of genomics and molecular tools is aiding in the identification of thermotolerant genes and pathways that could be targeted for strain improvement. Moreover, a 2024 market and regulatory report showed that microbial pesticides, particularly those based on EPF, comprised more than 55 % of global biopesticide sales, with strong market growth led by Asia and Latin America. This commercial success reflects increased farmer acceptance, improved formulation technologies and supportive regulatory frameworks in key agricultural regions (20).

Interestingly, a substantial number of fungal products, approximately 28 formulations, have been developed specifically as acaricides, all based on *Hirsutella thompsonii* Fisher. South American companies and research institutions have contributed significantly to global product development, accounting for nearly 43 % of all mycoinsecticide products. Regarding formulation types, the most common include technical concentrates containing fungus-colonised substrates (26.3 %), wettable powders (20.5 %) and oil dispersions (15.2 %) (18). Other less frequently used formulations comprise granules (2.9 %), technical materials (2.9 %), baits (1.8 %), water-dispersible granules (1.8 %), oil-miscible flowable concentrates (1.2 %), ultra-low volume (ULV) suspensions (0.6 %), suspension concentrates (0.6 %) and contact powders (0.6 %). A detailed list of commercially available mycoinsecticides, their target pests and the corresponding crops is provided in Table 3.

Mycoinsecticides constitute a significant component of

Table 2. Entomopathogenic fungi (EPF) acting as endophytes and their effects on insect pests

Entomopathogenic fungi (EPF)	Host plant	Target insect pest	Observed effect	Reference
Metarhizium anisopliae	Cotton	*Helicoverpa armigera*	Systemic colonisation led to reduced oviposition and larval survival; it produced insecticidal metabolites	(2)
Metarhizium robertsii	Soybean	*Aphis glycines*	Root endophyte; reduced aphid infestation and enhanced nutrient uptake	(2)
Lecanicillium longisporum	Cucumber	*Aphis gossypii*	Simultaneous suppression of aphid population and powdery mildew; enhanced plant tolerance	(3)
Beauveria bassiana	Mustard	*Lipaphis erysimi*	Significantly reduced aphid population under field conditions; effective biological control agent	(15)

Table 3. Entomopathogenic fungal products with their target pests and application areas

Fungus	Product name	Target pests	Application area	References
Nomuraea rileyi	BioPower	Tobacco caterpillar	Pulses	(21)
Metarhizium anisopliae	BioBlast	Termites	Houses (structural use)	(21)
Metarhizium anisopliae	Bio Magic	Brown planthopper (BPH)	Rice	(21)
Metarhizium anisopliae var. *acridum*	Green Muscle	Locusts	Natural bushland	(22)
Isaria fumosorosea	PFR-97	Whiteflies, thrips	Greenhouse crops	(22)
Beauveria bassiana	Mycotrol/Botanigard	Whiteflies, aphids, thrips	Greenhouse tomato, ornamentals	(23)
Beauveria bassiana	Naturalis	Sucking insects	Cotton	(23)
Beauveria bassiana	Betal	Scarab beetle larvae	Sugarcane	(23)
Beauveria bassiana	Ostrinol	Corn borer	Maize	(23)
Lecanicillium longisporum	Vertalec	Aphids	Greenhouse crops	(24)
Lecanicillium muscarium	Mycotal	Whiteflies, thrips	Greenhouse crops	(24)
Hirsutella thompsonii	Mycohit	Mites	Citrus	(25)

biopesticides developed and marketed for pest management. Although biopesticides currently account for only 3 % of the global crop protection market, the sector is experiencing a steady annual growth rate of 10 %, highlighting their increasing importance in IPM strategies (26). Within the global biopesticide market, mycoinsecticides represent the second-largest segment (27 %) after *B.t huringiensis*-based products (27). These fungal-based biopesticides are primarily produced in the Americas, Europe and Asia. In China alone, over 30 mycoinsecticide formulations have been registered, with *B. bassiana* being the most widely used species, available in multiple products targeting pests such as locusts, pine caterpillars and diamondback moths (28). *M. anisopliae* and *Purpureocillium lilacinum* are also commercially available, with several products targeting whiteflies, aphids and corn borers.

Application methods of EPF in insect pest suppression

Foliar spray

Fungal formulations such as WP (wettable powder) and EC (emulsifiable concentrate) are diluted in water and sprayed directly onto the aerial parts of the plants using sprayers. This method is effective for controlling foliar pests like whiteflies, aphids, thrips and caterpillars that feed and reproduce on leaves, stems and flowers. Crops such as tomato, cotton, brinjal and okra commonly benefit from this method. Adequate leaf coverage and suitable relative humidity are essential for spore germination and infection (29).

Soil application

Formulations like GR (Granules), WP or SC (suspension concentrate) are applied to the soil either by broadcasting or mixing with organic manures like FYM (farm yard manure) or compost. This approach is primarily used to manage soil-dwelling insect pests such as termites, root grubs and weevils, which are difficult to target through foliar methods. The fungal spores persist in the soil, creating a suppressive environment for pest emergence.

Seed treatment

In this method, seeds are coated with fungal spores using WP or DS (dustable powder) formulations before sowing. This ensures early protection of seedlings from pests such as cutworms, wireworms and shoot borers that attack during the initial growth stages. Additionally, it facilitates early establishment of beneficial fungi in the rhizosphere, which can contribute to improved plant health and stress tolerance (2).

Autodissemination devices

These devices are designed to attract specific insect pests using pheromones or food-based lures and are coated with dry conidia or fungal dusts. When insects such as fruit flies, houseflies, or mosquitoes enter the device, they become contaminated with fungal spores. After leaving the device, they carry the pathogen back to their populations, initiating horizontal transmission and causing epizootics.

Bait or trap application

In this technique, fungal spores are incorporated into food-based baits or attractant gels, which lure insects like ants, cockroaches and termites. Upon feeding or contact, the pests become infected and may mechanically spread the fungus within their colony or group. This method is particularly useful for managing pests in enclosed environments such as homes, godowns and storage facilities (30).

Challenges in the application of EPF for pest management

One of the primary challenges in using EPF for pest management is their relatively slow speed of action compared to chemical insecticides. While synthetic pesticides can kill pests within hours, EPF often require several days to infect, colonise and ultimately kill the target insect. This delay in action may not be suitable in situations where immediate pest suppression is necessary, particularly during severe infestations or in high-value crops where economic thresholds are low. Environmental sensitivity poses another major limitation. The efficacy of EPF is heavily influenced by climatic factors such as temperature, humidity and ultraviolet (UV) radiation. Most EPF perform optimally under moderate temperatures and high humidity, which restricts their effectiveness in arid or highly variable climatic zones. UV radiation, in particular, can rapidly degrade fungal conidia, reducing their persistence and field efficacy.

The formulation and shelf-life of EPF-based products present additional hurdles. Unlike chemical pesticides, fungal spores are living organisms that require specific conditions for viability and storage. Inadequate formulation can lead to poor spore stability, contamination and reduced shelf life. Maintaining viability over extended periods, especially in tropical climates without refrigeration, is a challenge that affects both transportation and farmer adoption. Mass production and commercialisation of EPF at an industrial scale remain complex. Culturing fungi requires specialised equipment, sterile conditions and cost-effective substrates, which may not be readily available or economically viable in all regions. Ensuring consistent spore quality and virulence across batches is essential for field performance but difficult to standardise in low-cost production systems.

Limited awareness and acceptance among farmers and extension personnel also hinder widespread adoption. Many users are unfamiliar with the specific conditions required for EPF to work effectively and may misuse the product, leading to disappointing results. Additionally, because fungal biopesticides act more slowly and subtly than chemical alternatives, users may perceive them as less effective without understanding their long-term benefits. Lastly, regulatory challenges and a lack of policy support can impede the registration and promotion of fungal biopesticides. In many countries, the approval process is designed around chemical pesticides and does not accommodate the unique properties of biological agents, causing delays and increased costs in bringing products to market. Addressing these regulatory gaps is critical for promoting wider adoption of EPF in pest management (3).

Future trends in entomopathogenic fungi

Enhanced strain development

The development of highly effective EPF strains will continue to be a major focus. Selective breeding and genetic improvement can enhance virulence against target pests while maintaining safety for non-target organisms. Future strains may also be engineered to tolerate extreme environmental conditions, such as high temperatures, UV exposure, or varying humidity, making them suitable for broader geographic and seasonal applications.

Innovative formulations and delivery systems

Advances in formulation technology will increase the stability, persistence and ease of application of EPF. Techniques such as microencapsulation, oil-based formulations and slow-release granules can protect fungal spores from environmental stress, extend shelf life and improve their adherence to crops or pest surfaces. Additionally, integration with modern delivery systems like drones or smart spraying technologies can make the EPF application more precise and cost-effective.

Synergistic integration with other pest management tools

Future approaches will increasingly combine EPF with other biological control agents, semiochemicals, or environmentally friendly insecticides. Such integration can improve pest suppression, delay resistance development and maintain ecosystem balance. Combining EPF with plant growth-promoting microbes could also enhance plant health and resilience while controlling pests.

Data-driven and precision applications

Comprehensive databases and predictive modelling of EPF species, insect hosts and environmental interactions will allow for targeted and site-specific applications. Precision agriculture tools, such as GIS mapping and pest population modelling, can optimise timing, dosage and location of EPF deployment, improving efficiency and reducing costs.

Interdisciplinary research and policy support

Progress in EPF applications will depend on collaboration among microbiologists, entomologists, agronomists and policymakers. Research will focus on understanding EPF ecology, host-pathogen interactions and climate adaptability. Policy support for registration, commercialisation and farmer training will be critical to ensure the wide adoption of EPF-based pest management.

Public awareness and farmer adoption

Future trends also include increased outreach to farmers and stakeholders to promote the benefits of EPF as a sustainable alternative to chemical pesticides. Training programs, demonstration plots and extension services will help build confidence in EPF products and encourage their integration into routine pest management practices.

Climate-resilient pest management

As climate change alters pest dynamics, EPF with higher tolerance to temperature and humidity extremes will be critical. Research will focus on identifying strains capable of surviving under changing climatic conditions and controlling pests that expand into new areas due to global warming.

Conclusion

Insect pest management is undergoing a paradigm shift toward sustainable and environmentally benign approaches, with EPF emerging as promising biological control agents. These fungi offer unique advantages over conventional pesticides, such as their ability to infect hosts via direct contact, their environmental safety and their compatibility with IPM systems. Widely studied genera like *Beauveria*, *Metarhizium*, *Isaria* and *Lecanicillium* have demonstrated significant efficacy against a diverse group of insect pests, particularly soft-bodied insects such as aphids, thrips and whiteflies. However, increasing research is also exploring their potential against hard-bodied pests such as beetles and borers. Despite their laboratory success, inconsistent field performance, often influenced by temperature, humidity and UV exposure, remains a major constraint. This highlights the need for selecting or engineering fungal strains with improved thermotolerance and UV resistance. Recent advances in molecular biology, genomics and bioformulation techniques are helping overcome these limitations and enhance the field viability of EPF. Furthermore, the increasing global demand for sustainable pest control has spurred market growth, with fungal-based biopesticides now accounting for more than 20–30 %, depending on classification, particularly in Asia and Latin America. In future, locally adapted strains, improved formulations and favourable regulatory frameworks will be key to unlocking the full potential of entomopathogenic fungi. With continued innovation and strategic implementation, EPF are poised to become a cornerstone component of sustainable pest management in both conventional and organic agricultural systems.

Authors' contributions

KKD and VKM wrote and drafted the manuscript. SY guided the corrections and improvements. SKS, SP and MSD collected literature and helped in formatting. All authors read and approved the final draft.

Compliance with ethical standards

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