Mycopesticide as a Natural Enemy for Sustainable Pest Management

Shaizee[1]
[1]Insect EcoDevo Lab, Integral Centre of Excellence for Interdisciplinary Research (ICEIR)-8, Department of Bioscience, Integral University, Lucknow (India)

Salman Ahmad[2]
[2]Department of Agriculture, Integral Institute of Agricultural Sciences and Technology (IIAST), Integral University, Lucknow (India)

Arshi Siddiqui[1]*
Department of Bioscience, Integral University, Lucknow (India)

*Corresponding author- Dr. Arshi Siddiqui, Email: arshi.apda@gmail.com

Abstract— *The increasing concerns about synthetic pesticides highlight the need for sustainable pest management. Entomopathogenic fungi (EPF) sustain their eco-friendly status for use in an IPM approach. These soil microbes penetrate protected cuticles of arthropod pests using toxins and enzymes to infect and kill their hosts. There are over 700 fungal species known to behave as this way. EPF pose no great harm to the environment, unlike synthetic pesticides. In addition, they are host-specific and limit the prospects for pest resistance-powerful weapons for pest-control. However, promising they may be, drawbacks to their use remain, such as their sensitivity to environmental conditions, short shelf-life, slow action, and considerable costs of production. Stronger virulent strains, better formulations, and genetic modifications are being worked upon in recent years to overcome such constraints, thus allowing holistic incorporation of EPF into IPM programs and their synergistic mixtures.*

Keywords— *Entomopathogenic fungi, Mycoinsecticide, Endophyte, Biological control.*

I. INTRODUCTION

The increasing awareness about environmental and health hazards of synthetic pesticides has made it more important to find the ecologically safe and sustainable pest management technologies [1]. The heavy use of synthetic pesticides has been cited as being detrimental to biodiversity, nothing that non-target species such as pollinators and natural pests' enemies could be affected [2]. Furthermore, through the continuous application of these chemicals, insect pests have evolved the frightening phenomenon of resistance and the traditional control is becoming more and more ineffective. This resistance necessitates an urgent search for, and implementation of, alternative and environmentally friendly pest control measures. Faced with all these challenges, there is a growing global trend towards eco-friendly, sustainable agriculture that takes a long-term view of food security and healthy ecosystem preservation. Sustainable management of pests is one of the core concepts of this movement that managing agricultural pests while minimizing the influence on the environment [3].

Entomopathogenic fungi (EPF) are an innovative group of natural pest managers that are increasingly becoming the talk of the town in the realm of sustainable agriculture. These exceptional fungi have the special privilege of infecting and eventually killing arthropod pests, hence acting as useful natural predators in combat against agricultural loss [4]. In fact, EPFs are critical regulators of insect populations in natural ecosystems and provide a biological means for controlling pests that can be utilized in agriculture. Their utility as biopesticides, biologicals specifically utilized for pest management, makes them central elements of integrated pest management (IPM) strategies [5]. IPM is a comprehensive method that blends different pest control strategies, focusing on ecological integrity and reduced usage of chemical pesticides. Of the varied range of EPF, a number of genera have proven to be especially important in pest control, among them being Beauveria, *Metarhizium*, *Lecanicillium*, *Isaria*, *Cordyceps*, *Entomophthora*, *Nomuraea*, *Hirsutella*, *Neozygite*s, and *Tolypocladium*. Each of these genera contains species with different host ranges and modes of action, demonstrating the extensive diversity within this group of natural pest control agents [4].

The following review possible to introduce entomopathogenic fungi as the most potent natural enemies in achieving these objectives. It will cover their taxonomic diversity, the complicated modes of action, the advantages against conventional chemical insecticides as well as extensive applications in agriculture. In addition, current obstacles and constraints in the use of EPF will be discussed and the most recent findings and potential future directions in this exciting area of research will be overviewed. Finally, this review aims to emphasize the priority of EPF, thereby reducing our reliance on synthetic chemical pesticide, favouring the development of an environmentally compatible agriculture in reaching simultaneously food security and the good ecologic state.

II. DIVERSITY AND CLASSIFICATION OF ENTOMOPATHOGENIC FUNGI

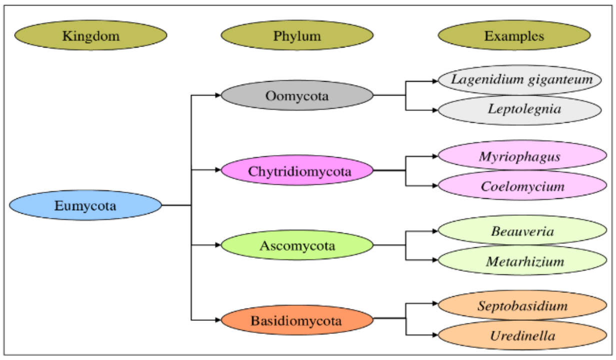

Fig 1. Classification of entomopathogenic fungi.

Entomopathogenic fungi are categorized in 4 classes: Oomycetes, Chytridiomycota, Basidiomycota, and the most common Ascomycota [6]. This broad phylogenetic distribution indicates that the capacity to infect insects has independently evolved across multiple lineages within the fungal kingdom. Historically, the group Deuteromycota also encompassed many significant EPF; however, advancements in molecular phylogenetics have led to the reclassification of most of these fungi within the Ascomycota [7]. The sheer number of identified insect-pathogenic fungi is staggering, with over 700 species described across approximately 90 different genera. This extensive diversity underscores the vast potential reservoir of EPF that can be explored and harnessed for the development of novel and effective biocontrol agents [8].

Some of the main genera of EPFs are prioritized because of their effective implementation and widespread use for integrated pest management. *Beauveria* is a good example; especially the species *B. bassiana*, because of its wide spectrum of insects it controls-butterflies, aphids, thrips, grasshoppers, and beetles [9]. White muscardine disease has been extensively researched for foliar application and as an endophyte colonizing the plant tissue to cumulatively provide systemic protection upon infection in an insect host [10]. *Metarhizium*, obviously, is the other important fungus, with *Metarhizium anisopliae* being the most famous species known as the green muscardine fungus [11]. *Metarhizium* is effective against a variety of insects but is especially noted for attacking soil-inhabiting pests such as beetles, root weevils, flies, thrips, and gnats. Its uses are also extended by its endophytic potential in crops such as citrus and maize [12]. The other important genus is *Lecanicillium*, once called *Verticillium lecanii*, which mainly attacks sucking insects such as aphids, scales, whiteflies, and mealybugs. Being under Order Hypocreales, *Lecanicillium* has been formulated and marketed into commercial mycoinsecticides, validating the usefulness of *Lecanicillium* in the control of these often-difficult pests. The genus *Isaria*, with species such as *Isaria farinosa* and *Isaria fumosorosea*, recognizes a wider host range with a particular preference for Lepidopteran insects. *Isaria fumosorosea* stands out as a biocontrol agent for being effective against pests like whiteflies, thrips, aphids, and termites [4]. An exceedingly aggressive group of EPF exists within the Class Entomophthorales, including some of its genera, such as *Entomophthora*, *Conidiobolus*, *Erynia*, *Zoophthora*, and *Entomophaga*. These fungi specialize in particular groups of insects, such as aphids and grasshoppers, and while they are most successful, in practice, their application can be hindered due to difficulties in their laboratory cultivation. Some other major genera that contribute to the diversity of EPF include *Hirsutella*, against mites, *Neozygites*, against mites, *Nomuraea rileyi*, against lepidopteran pests, and *Tolypocladium*, against mosquito larvae. This complete list of major genera, each with its own set of target pests and characteristics of ecosystems, indicates the feasibility of selecting specific EPF to achieve desired and sustainable pest control in diverse agricultural ecosystems [13].

III. MECHANISM OF ACTION: THE ENTOMOPATHOGENIC INFECTION PROCESS

These fungi are able to parasitize susceptible hosts via direct penetration of the cuticle with the initial and potentially determining interaction occurring between the fungal spore and the insect epicuticle [14].

This initial, essential step is supported by a synergy between hydrophobic and electrostatic forces that induce adhesion between the spore and the epicuticle of the insect. In addition, the activation of several lytic enzymes and secondary metabolites is involved in solidifying this attachment. After successful attachment, the conidia germinate on the insect body surface, a process that includes sprouting and the production of special structures known as appressoria [15].

High relative humidity (RH) is required for optimum germination of fungal conidia, as 100% RH has been found to be the most suitable for fungal spore germination and intermediate temperature ranging from 15°C to 30°C for optimal activity. Such environmental requirements highlight one potential hurdle in delivering consistent efficacy in the field where such conditions cannot always be guaranteed. After germination of the fungus, it has to break through the insect's hard outer cover, the cuticle [16].

EPF exerting strong mechanical pressure on the insect’s cuticle -degrading enzymes, such as chitinases, lipases, and proteases. These enzymes easily digest the various layers of the insect exoskeleton, opening the door for the fungus to invade the haemolymph, the circulatory fluid of the insect. Once the fungus has gained entry into the haemolymph, it grows exceptionally fast, usually converting into hyphal bodies or blastospores, which are single-cell spores specifically suited for growth within the internal environment of the insect. The fungus then becomes systemically distributed within the body of the insect, infecting different tissues and organs. This widespread colonization impedes normal physiological processes in the insect, resulting in a chain reaction of harmful effects [17].

Aside from direct invasion of the tissue, a lot of EPF generate a range of highly toxic compounds, including bassianolides, beauvericin, and destruxins, that are directly involved in killing the host. These toxins can interfere with essential physiological functions and repress the immune system of the insect, adding to the virulence of the pathogen. The time from when the insect infects with the fungal pathogen to when it will ultimately die is referred to as the lethal infection time, the length of which can be variable in terms of the particular fungal species, the insect host, and prevailing environmental conditions [18].

After the death of the insect, the fungus grows out of the insect cadaver in a saprophytic growth phase during which it still uses the dead insect as a nutrient source. In favourable environmental conditions, the fungus later forms new fungal spores (conidia) on the surface of the dead insect [19]. These spores then get scattered, infecting other insects that are vulnerable, which keeps the cycle going. Things like water and wind really help spread the fungal spores across insect populations. One of the nice things about entomopathogenic fungi (EPF) is that they can reproduce and, after killing their host, they keep going without needing any help. This makes them pretty useful for long-term, self-sustaining pest control [20].

IV. ADVANTAGES OF ENTOMOPATHOGENIC FUNGI IN SUSTAINABLE PEST MANAGEMENT

Entomopathogenic fungi have several advantages over conventional insecticides, including cost-effectiveness, high yield, absence of harmful side-effects for beneficial organisms, fewer chemical residues in the environment and increased biodiversity in ecosystems [21]. While the possibility of mycotoxin production by certain EPF exists, most mycoinsecticides are low-risk and are not likely to find their way into the food chain via this pathway. This lower environmental burden and improved safety make EPF a preferable choice for environmentally friendly agricultural methods [22].

Another major benefit of EPF is their commonly high level of target specificity. Numerous EPF have a restricted host range, which means that they can act effectively against specific insect pests or pest groups without harming other organisms significantly. Such specificity reduces disturbance to the overall ecosystem in contrast to broad-spectrum chemical insecticides that may act indiscriminately on a variety of insects, including those that are beneficial. By projecting their influence on the intended pests, EPF help in maintaining biodiversity, which is an important component of ecological sustainability [23]. Additionally, the likelihood of developing resistance in insect pests against EPF is normally lower than with synthetic pesticides [24].

This is due to the complicated mode of action of EPF, which typically entails several enzymes and toxins that target the insect via several avenues. This multi-mode attack presents more difficulties in the evolution of practical resistance mechanisms among pests. At times, EPF have even been effective against pest populations already resistant to chemical control, showcasing their potential in overcoming the increasing threat to pest control [6].

Aside from their direct effects on pests, certain endophytic EPF may provide other advantages to plants, such as the stimulation of plant growth, improved nutrient acquisition, increased root hair density, and general enhancement of plant well-being. They may also trigger systemic resistance in plants, thereby reducing their susceptibility to both insect pests and plant pathogens [21]. In addition, endophytic EPF are capable of modifying secondary metabolites of the plant and volatile organic compound emission, thus reinforcing the natural resistance of the plant to herbivorous insects. Through these two advantages of pest management and plant health improvement, more robust and productive agricultural systems are developed [25].

Lastly, EPF have the long-term potential for pest management. They can remain in the environment and in plant systems as endophytes, conferring extended protection against insect pests [26]. Their capacity to reproduce via sporulation following host killing can result in long-term suppression of pest populations. This regenerative potential can cut down on the number of applications needed compared to certain chemical pesticides, possibly saving money and being more efficient in the long term [15].

V. PRACTICAL USES AND CASE STUDIES OF ENTOMOPATHOGENIC FUNGI

The field uses of entomopathogenic fungi are various and have shown substantial success in managing a broad range of economically valuable insect pests on many crops.

Table 1: Selected Case Studies of Entomopathogenic Fungi in Pest Management

Crop	Target Pest	EPF Species Used	Application Method	Key Outcome/Results	References
Citrus	Citrus greening disease vector (*Diaphorina citri*)	*Beauveria bassiana*	Foliar Endophyte	Growth suppression of three successive generations of the vector.	[27]
Maize	Stem borers (*Chilo partellus*)	*Beauveria bassiana*	Endophyte	Susceptibility in stem borers.	[28]
Corn	Fall armyworm (*Spodoptera frugiperda*)	*Beauveria bassiana*	Endophyte	Reduced larval growth, pupal survival, developmental stages, lifespan, and reproductive success.	[29]
Locusts	Oriental migratory locust Locust (*Locusta migratoria manilensis*)	*Metarhizium anisopliae*	Foliar	70–80% mortality in lab (4th instars); 65–97% population decline in field within 8–11 days.	[30]

Potato	Colorado potato beetle (*Leptinotarsa decemlineata*)	*Beauveria bassiana*	Foliar	Repeated applications reduced adult emergence by ~80% (58–93%).	[31]
Coffee	Coffee berry borer (*Hypothenemus hampei*)	*Beauveria bassiana*	Endophyte	Reported to control the coffee berry borer.	[32]
Tomato	Tomato leaf miner (*Tuta absoluta*)	*Beauveria bassiana*	Endophyte	Showed both epiphytic and endophytic activity against this pest.	[33]
Sweet Pepper	Green peach aphids (*Myzus persicae*)	*Amanita muscaria*	Endophyte	Altered the life cycle and behavioral response of the aphid.	[34]
Horticultural crop	Aphids (various horticultural crops)	*Metarhizium anisopliae, Beauveria bassiana*	Foliar	Dominantly used as biopesticides, leading to increased demand with over 132,980 hectares under use in 2019.	[35]

VI. CHALLENGES AND LIMITATIONS IN THE USE OF ENTOMOPATHOGENIC FUNGI

Although there are many benefits of entomopathogenic fungi to sustainable pest control, there are also some challenges and limitations to their wide use. Their sensitivity to environmental factors is one such limitation. The effectiveness of EPF is very much dependent upon conditions like temperature, humidity, and ultraviolet (UV) light [27].

Low humidity rates and temperatures beyond the ideal range tend to lower their capacity to infect and kill the pests. In addition, UV exposure can adversely affect the viability and performance of fungal spores. Such environmental dependency may result in inconsistency in pest control performance under varying field conditions [16].

The second challenge is the shelf life and formulation of EPF-based biopesticides. The shelf life of the fungal inoculum in commercial formulation might be constrained to between three and six months, requiring proper storage and timely use. Formulating strong and economical products that are capable of sustaining their performance under various environmental conditions is still an area of research. Although methods such as cryopreservation and oil-based formulation may enhance shelf life and stress tolerance, they are potentially detrimental to spore germination and adhesion, decreasing overall effectiveness [36].

Relative to synthetic insecticides, EPF tend to have a slower rate of action, normally taking two or three weeks to bring about adequate control of insect pest populations. Such slow action could be inadequate for applications where there is an immediate need for pest elimination in order to avoid causing extensive and severe crop damage [37].

Commercially available EPF strains could also be a limitation in terms of cost and availability of EPF formulations available. The cost of EPF products versus those of synthetic chemical insecticide is frequently higher, this factor is a lot of concern to farmers and more particularly in the developing countries. Furthermore, EPF products may be less accessible and less widely available in some regions, which also hinders adoption [38].

The effectiveness of EPF may also differ based on a number of factors such as the type of fungal strain applied, the pest species being targeted, prevailing environmental conditions, and methods of application used. Consistent and effective control of pests under varied field conditions can prove to be a major challenge [39].

VII. RECENT ADVANCEMENTS AND FUTURE PROSPECTS IN ENTOMOPATHOGENIC FUNGI RESEARCH

Nowadays, recent advances in entomopathogenic fungi research are expanding continuously their possibilities as environmentally friendly pest control agents. Continued discovery and characterization of new species and strains of EPF is anticipated to bring forth increased virulence agents with broader host range and tolerance of higher environmental extremes. For example, recent investigations have led to the identification of new species in *Diversispora* and *Scutellospora* genera [40]. These findings widen the existing biocontrol toolset and provide the potential to discover solutions to a broader range of agricultural pests [41].

The use of new biotechnological measures is becoming an ever-more crucial role in increasing the effectiveness and virulence of EPF. Genetic engineering methods and induced mutation are being developed to enhance fungal strains, enhance the speed of their mode of action, and increase their endurance in harsh environmental conditions [42]. The construction of recombinant endophytic microorganisms to produce anti-pest proteins is also becoming increasingly popular as an effective approach for insect pest control [43].

Substantial advances are being made in the formulation and application technology of EPF. Developments are aimed at the formulation of extended shelf-life products, better stability under field conditions, and enhanced spore germination and attachment to insect cuticles. Emulsifiable oil-based formulations and vegetable oils are being explored to increase tolerance in fungal spores to both temperature extremes and lethal UV radiation [44]. Additionally, nanotechnology is being considered as a vehicle for making EPF delivery and overall performance better [45]. New application techniques, including autodissemination methods along with semiochemicals that lure the pests, are also being explored to improve the efficacy of pest control [46]. Better comprehension of the complex relationships between EPF and insect hosts is important for improving more effective and sustainable biocontrol strategies. Continuing research seeks to demystify the molecular processes driving fungal pathogenicity, insect host immune systems, and pest susceptibility to resistance to EPF [47]. Research into the symbiotic bacteria's role in modulating insect susceptibility to EPF infection is also yielding useful information. Learning how EPF suppresses the immune systems of insect pests is another prime area of ongoing research [48].

Lastly, an increasing focus is put on the integration of EPF with other biocontrol agents and in holistic IPM programs. Further research is investigating the compatibility and synergistic potential of integrating EPF with natural enemies like predators, parasitoids, and entomopathogenic nematodes. Improving the incorporation of EPF into large-scale IPM programs is significant in minimizing reliance on traditional chemical pesticides and increasing ecologically harmonious pest management systems [49, 50].

VIII. CONCLUSION

Entomopathogenic fungi (EPF) are a unique group of fungi that act as natural enemies to insects. They have emerged as an essential tool in integrated pest management (IPM), offering a sustainable and environmentally friendly alternative to chemical pesticides. These fungi, including *Beauveria bassiana*, *Metarhizium anisopliae*, and *Lecanicillium lecanii*, infect insects through direct contact, penetrating their cuticles, proliferating internally, and eventually killing the host. They are known for their host specificity, minimal impact on the environment, and capacity to induce plant resistance mechanisms. Many case studies confirm their success in managing crop pests in varied agro-ecological zones. Despite these advantages, challenges such as sensitivity to environmental factors like temperature, humidity, and UV radiation, as well as limitations in shelf life and field persistence, continue to limit their effectiveness. Their slower action compared to chemicals and occasional non-target effects require ongoing improvements. Advances in formulation technologies and molecular tools are enhancing the efficacy and adaptability of EPF supporting their broader application in pest management. Further studies must focus on increasing stress tolerance, improving cost-effectiveness, and integrating EPF into IPM with other biocontrol agents. By refining these aspects, EPF can play a significant role in reducing chemical pesticide usage and promoting ecological stability in agriculture.

ACKNOWLEDGMENT

The authors are thankful to the Hon'ble Vice-Chancellor, Integral University, Lucknow for the necessary infrastructure support and the Dean office, R&D, Integral University.

REFERENCES

[1] P. Satyanarayana, T. Guhan, T. Ganesan, A. Bhagyalakshmi, L. Pallavi, A. K. Koshariya, and A. Rajaram, "Exploring the impact of pesticide resistance in agricultural pest management," Glob. Nest J, vol. 26, no. 9, 2024.

[2] N. F. Wan, L. Fu, M. Dainese, L. P. Kiær, Y. Q. Hu, F. Xin, and C. Scherber, "Pesticides have negative effects on non-target organisms," Nat. Commun, vol. 16, no. 1, p. 1360, 2025.

[3] W. Zhou, M. Li, and V. Achal, "A comprehensive review on environmental and human health impacts of chemical pesticide usage," Emerg. Contam, p. 100410, 2024.

[4] A. Sharma, S. Sharma, and P. K. Yadav, "Entomopathogenic fungi and their relevance in sustainable agriculture: A review," Cogent Food Agric, vol. 9, no. 1, p. 2180857, 2023.

[5] J. Shang, G. Tang, M. Lu, and C. Wang, "Host and environmental sensing by entomopathogenic fungi to infect hosts," Curr. Clin. Microbiol. Re, vol. 9, no. 4, pp. 69–74, 2022.

[6] A. Litwin, M. Nowak, and S. Różalska, "Entomopathogenic fungi: unconventional applications," Rev. Environ. Sci. Biotechnol, vol. 19, no. 1, pp. 23–42, 2020.

[7] J. P. Araújo and D. P. Hughes, "Diversity of entomopathogenic fungi: which groups conquered the insect body?," Adv. Genet, vol. 94, pp. 1–39, 2016.

[8] D. K. Chaurasiya, S. Singh, M. Kumar, A. P. Singh, and S. Sahni, "Chapter-4 Bio-Control of Insect Pests through Entomopathogenic Fungi: A Novel Approach," Curr. Res. Innov. Plant Pathol, vol. 27, p. 77, 2021.

[9] P. Saranraj and J. Arul, "Agrobeneficial entomopathogenic fungi – *Beauveria bassiana*: A review," Int. Adv. J. Mod. Res, vol. 3, no. 2, pp. 1051–1087, 2017, doi: 10.22192/iajmr.2017.3.2.4.

[10] A. Bahadur, "The potential of the entomopathogenic fungus *Beauveria bassiana* to manage insect pests and diseases," Nat. Resour. Conserv. Res, vol. 6, no. 2, p. 2543, 2023, doi: 10.24294/nrcr.v6i2.2543.

[11] Z. Y. Peng, S. T. Huang, J. T. Chen, N. Li, Y. Wei, A. Nawaz, and S. Q. Deng, "An update of a green pesticide: *Metarhizium anisopliae*," All Life, vol. 15, no. 1, pp. 1141–1159, 2022.

[12] L. B. Stone and M. J. Bidochka, "The multifunctional lifestyles of *Metarhizium*: evolution and applications," Appl. Microbiol. Biotechnol, vol. 104, no. 23, pp. 9935–9945, 2020.

[13] G. A. Bugti, B. Wang, S. A. Memon, G. Khaliq, and M. A. Jaffar, "Entomopathogenic fungi: factors involved in successful microbial control of insect pests," J. Entomol, vol. 17, pp. 74–83, 2020.

[14] A. Ortiz-Urquiza and N. O. Keyhani, "Action on the surface: entomopathogenic fungi versus the insect cuticle," Insects, vol. 4, no. 3, pp. 357–374, 2013, doi: 10.3390/insects4030357.

[15] M. Ma, J. Luo, C. Li, I. Eleftherianos, W. Zhang, and L. Xu, "A life-and-death struggle: interaction of insects with entomopathogenic fungi across various infection stages," Front. Immunol, vol. 14, p. 1329843, 2024.

[16] S. A. Syazwan, S. Y. Lee, A. S. Sajap, W. H. Lau, D. Omar, and R. Mohamed, "Interaction between *Metarhizium anisopliae* and its host, the subterranean termite *Coptotermes curvignathus* during the infection process," Biology, vol. 10, no. 4, p. 263, 2021.

[17] N. Pedrini, "Molecular interactions between entomopathogenic fungi (Hypocreales) and their insect host: perspectives from stressful cuticle and hemolymph battlefields and the potential of dual RNA sequencing for future studies," Fungal Biol, vol. 122, no. 6, pp. 538–545, 2018.

[18] C. Filippou, R.H. Coutts, I. Kotta-Loizou, S. El-Kamand, and A. Papanicolaou, "Transcriptomic analysis reveals molecular mechanisms underpinning mycovirus-mediated hypervirulence in *Beauveria bassiana* infecting *Tenebrio molitor*," J. Fungi, vol. 11, no. 1, p. 63, 2025.

[19] T. Abdelghany, Entomopathogenic Fungi and Their Role in Biological Control, 2018.

[20] S. Mantzoukas, F. Kitsiou, D. Natsiopoulos, and P. A. Eliopoulos, "Entomopathogenic fungi: interactions and applications," Encyclopedia, vol. 2, no. 2, pp. 646-656, 2022.

[21] S. Mantzoukas and P. A. Eliopoulos, "Endophytic entomopathogenic fungi: A valuable biological control tool against plant pests," Appl. Sci, vol. 10, no. 1, p. 360, 2020.

[22] A. Hussain, M. Rizwan-ul-Haq, H. Al-Ayedh, and A. AlJabr, "Mycoinsecticides: Potential and Future Perspective," Recent Pat Food Nutr Agric, 2014. doi: 10.2174/2212798406666140613113905.

[23] W. Islam, M. Adnan, A. Shabbir, H. Naveed, Y. S. Abubakar, M. Qasim, et al., "Insect-fungal-interactions: A detailed review on entomopathogenic fungi pathogenicity to combat insect pests," Microb. Pathog, vol. 159, p. 105122, 2021.

[24] M. Skinner, B. L. Parker, and J. S. Kim, "Role of entomopathogenic fungi in integrated pest management," in Integrated Pest Management, pp. 169-191, 2014.

[25] K. Aravinthraju, M. Shanthi, M. Murugan, R. Srinivasan, L. A. Maxwell, N. Manikanda Boopathi, and R. Anandham, "Endophytic Entomopathogenic Fungi: Their Role in Enhancing Plant Resistance, Managing Insect Pests, and Synergy with Management Routines," J. Fungi, vol. 10, no. 12, p. 865, 2024.

[26] Z. Xie, Y. Lu, Y. Tian, Q. Li, X. Zou, L. Sui, and Z. Zhang, "Fusarium citri as an entomopathogenic fungus mediating plant resistance against insect pests and phytopathogens," Sci. Rep, vol. 15, no. 1, p. 12957, 2025.

[27] B. S. Bamisile, C. K. Dash, K. S. Akutse, M. Qasim, L. C. Ramos Aguila, F. Wang, et al., "Endophytic Beauveria bassiana in foliar-treated Citrus limon plants acting as a growth suppressor to three successive generations of Diaphorina citri Kuwayama (Hemiptera: Liviidae)," Insects, vol. 10, no. 6, p. 176, 2019.

[28] W. B. A. Bancole, M. D. Laing, K. S. Yobo, A. Togola, and M. B. Saeed, "Investigating the endophytic competency and pathogenicity efficacy of Beauveria bassiana isolates against Chilo partellus Swinhoe," Int. J. Trop. Insect Sci, vol. 42, no. 2, pp. 1225-1237, 2022.

[29] M. L. Russo, L. R. Jaber, A. C. Scorsetti, F. Vianna, M. N. Cabello, and S. A. Pelizza, "Effect of entomopathogenic fungi introduced as corn endophytes on the development, reproduction, and food preference of the invasive fall armyworm Spodoptera frugiperda," J. Pest Sci, vol. 94, pp. 859-870, 2021.

[30] Z. Long and D. M. Hunter, "Laboratory and field trials of Green Guard® (Metarhizium anisopliae var. acridum) (Deuteromycotina: Hyphomycetes) against the oriental migratory locust (Locusta migratoria manilensis) (Orthoptera: Acrididae) in China," J. Orthoptera Res, vol. 14, no. 1, pp. 27-30, 2005.

[31] S. P. Wraight and M. E. Ramos, "Delayed efficacy of Beauveria bassiana foliar spray applications against Colorado potato beetle: impacts of number and timing of applications on larval and next-generation adult populations," Biol. Control, vol. 83, pp. 51-67, 2015.

[32] E. J. B. Ohoueu, N. Aby, D. Diabate, K. F. Yao, K. M. K. Gba, D. M. Sery, et al., "Efficacy of isolates of an entomopathogenic fungus on coffee berry borer," Afr. Crop Sci. J, vol. 32, no. 3, pp. 223-234, 2024.

[33] N. Allegrucci, M. S. Velazquez, M. L. Russo, M. E. Pérez, and A. C. Scorsetti, "Endophytic colonisation of tomato by the entomopathogenic fungus Beauveria bassiana: the use of different inoculation techniques and their effects on the tomato leafminer Tuta absoluta (Lepidoptera: Gelechiidae)," Mycol. Prog, vol. 16, no. 5, pp. 495-506, 2017.

[34] L. Wilberts, J. Vuts, J. C. Caulfield, G. Thomas, M. A. Birkett, B. Herrera-Malaver, et al., "Impact of endophytic colonization by entomopathogenic fungi on the behavior and life history of the tobacco peach aphid Myzus persicae var. nicotianae," PLoS One, vol. 17, no. 9, p. e0273791, 2022.

[35] K. S. Akutse, S. Subramanian, N. K. Maniania, T. Dubois, and S. Ekesi, "Biopesticide research and product development in Africa for sustainable agriculture and food security–Experiences from the International Centre of Insect Physiology and Ecology (icipe)," Front. Sustain. Food Syst, vol. 4, p. 563016, 2020.

[36] M. A. Ayala-Zermeño, A. M. Berlanga-Padilla, C. F. Regla-Márquez, G. J. Lino-López, F. Muñiz-Paredes, R. Montesinos-Matías, and J. A. Sánchez-González, "Long-term preservation and genetic stability of entomopathogenic fungal species," J. Microbiol. Methods, vol. 208, p. 106711, 2023.

[37] M. Ghorui, S. Chowdhury, and S. Burla, "The science behind entomopathogenic fungi: Mechanisms and applications," in Entomopathogenic Fungi: Prospects and Challenges, Singapore: Springer Nature Singapore, 2024, pp. 3-35.

[38] D. Singh, T. K. Raina, and J. Singh, "Entomopathogenic fungi: An effective biocontrol agent for management of insect populations naturally," J. Pharm. Sci. Res, vol. 9, no. 6, p. 833, 2017.

[39] R. Bava, F. Castagna, C. Piras, V. Musolino, C. Lupia, E. Palma, et al., “Entomopathogenic fungi for pests and predators’ control in beekeeping,” Vet. Sci, vol. 9, no. 2, p. 95, 2022.

[40] L. Lin, Y. Lin, N. O. Keyhani, H. Pu, J. Yang, C. Xiong, et al., “New entomopathogenic species in the Clavicipitaceae family (Hypocreales, Ascomycota) from the subtropical forests of Fujian, China,” Front. Microbiol, vol. 16, p. 1532341, 2025.

[41] P. Niezgoda, J. Błaszkowski, T. Błaszkowski, A. Stanisławczyk, S. Zubek, P. Milczarski, et al., “Three new species of arbuscular mycorrhizal fungi (*Glomeromycota*) and *Acaulospora gedanensis* revised,” Front. Microbiol, vol. 15, p. 1320014, 2024.

[42] B. Lovett and R. J. St. Leger, “Genetically engineering better fungal biopesticides,” Pest Manag. Sci, vol. 74, no. 4, pp. 781–789, 2018.

[43] X. Zhao, G. Qi, X. Zhang, N. Lan, and X. Ma, “Controlling sap-sucking insect pests with recombinant endophytes expressing plant lectin,” Nature Precedings, pp. 1, 2010

[44] T. Aquino-Bolaños, Y. D. Ortiz-Hernández, A. Bautista-Cruz, and M. A. Acevedo-Ortiz, “Viability of entomopathogenic fungi in oil suspensions and their effectiveness against the agave pest *Scyphophorus acupunctatus* under laboratory conditions,” Agronomy, vol. 13, no. 6, p. 1468, 2023.

[45] X. Kong, S. Tan, M. Guan, X. Lin, J. Shen, W. Shi, and D. Wang, “Nanocarrier-mediated transdermal delivery of Lmidgf4 dsRNA expedites biological control of locusts by *Beauveria bassiana*,” J. Nanobiotechnol, vol. 23, no. 1, p. 272, 2025.

[46] T. Tsutsumi, M. Teshiba, M. Yamanaka, Y. Ohira, and T. Higuchi, “Effect of an entomopathogenic fungus infection device using aggregation pheromone against the German-winged green stink bug, *Pentatomus germanica*,” Jpn. J. Appl. Entomol. Zool, vol. 47, no. 4, pp. 159–163, 2003.

[47] S. Hong, J. Shang, Y. Sun, G. Tang, and C. Wang, “Fungal infection of insects: molecular insights and prospects,” Trends Microbiol, vol. 32, no. 3, pp. 302–316, 2024.

[48] M. Liu, J. Ding, and M. Lu, “Influence of symbiotic bacteria on the susceptibility of *Plagiodera versicolora* to *Beauveria bassiana* infection,” Front. Microbiol, vol. 14, p. 1290925, 2023.

[49] A. A. Mohammed and P. E. Hatcher, “Combining entomopathogenic fungi and parasitoids to control the green peach aphid *Myzus persicae*,” Biol. Control, vol. 110, pp. 44–55, 2017.

[50] V. Půža and E. Tarasco, “Interactions between entomopathogenic fungi and entomopathogenic nematodes,” Microorganisms, vol. 11, no. 1, p. 163, 2023.