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BIOCONTROL BREAKTHROUGH: LEVERAGING ENTOMOPATHOGENS FOR ECO-FRIENDLY PEST MANAGEMENT IN MODERN AGRICULTURE

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Abstract

Agricultural systems worldwide face significant challenges from a myriad of pests, including insects, pathogens, weeds, and vertebrates, leading to substantial losses in crop yields. Chemical insecticides, while effective, have raised concerns due to resistance development and environmental harm. As a result, there's a growing interest in alternative pest management strategies, such as the use of entomopathogens. Entomopathogenic fungi (EPF), entomopathogenic nematodes (EPNs), entomopathogenic viruses (EPVs), and entomopathogenic bacteria offer promising alternatives to chemical insecticides. EPF and EPNs target a wide range of insect pests and play multifaceted roles beyond pest control, including disease suppression and plant growth promotion. EPVs exhibit specificity and low risk to non-target organisms, making them valuable assets in integrated pest management. Similarly, entomopathogenic bacteria, particularly *Bacillus thuringiensis*, offer effective pest control while minimizing environmental impact. Entomopathogens represent a sustainable approach to pest management in agriculture. Continued research into their biology, ecology, and practical applications is essential for optimizing their efficacy and integrating them into pest management programs effectively. By harnessing the potential of entomopathogens, we can address the challenges posed by chemical insecticides and promote sustainable agriculture.

Keywords: Entomopathogens, biological control, agriculture, pest management, entomopathogenic fungi, entomopathogenic nematodes, entomopathogenic viruses

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Introduction

Agricultural systems worldwide face significant challenges from a myriad of pests, including plant pathogens, weeds, arthropods, mollusks, and vertebrates (Mantzoukas and Eliopoulos, 2020). These pests collectively pose a threat to global food production by causing substantial losses in crop yields. It is estimated that agricultural pests have led to a staggering 40% reduction in potential world crop yields (Mantzoukas and Eliopoulos, 2020). Among these pests, insects play a particularly prominent role, accounting for approximately 10.80% of worldwide agricultural losses in the post-green revolution era (Dhaliwal et al., 2015). To mitigate these losses, farmers often resort to the use of chemical insecticides due to their ease of application and high efficacy (Sharma, 2019). However, the widespread and intensive use of insecticides has led to the development of resistance in pest populations, with resistance documented in up to 80% of cases (Sharma, 2019). In response to these challenges, there has been growing interest in alternative pest management strategies, including the use of entomopathogens—microorganisms that naturally regulate insect pest populations (Roy and Cottrell, 2008). These biological control agents offer a promising avenue for sustainable pest management, providing effective control of insect pests while minimizing environmental harm and reducing reliance on chemical insecticides.

Entomopathogenic fungi (EPF) represent a vital component of biological pest management strategies worldwide. These organisms, characterized as heterotrophic, eukaryotic, and either unicellular or multicellular (filamentous), play a crucial role in regulating insect populations (Bahadur, 2018). EPF exhibit varying reproductive strategies, including sexual, asexual, or both, and produce a diverse array of infective propagules. Environmental factors such as UV light, temperature, and humidity significantly influence the efficacy of EPF in the field. EPF is found in several orders, including Hypocreales, Onygenales (Ascosphaera genus), Entomophthorales, and Neozygitales of the Entomophthoromycota class (Sung et al., 2008).

Notable genera of EPF include Metarhizium, Beauveria, Verticillium, Nomuraea, Entomophthora, and Neozygites, which encompass a wide taxonomic range (Deshpande, 1999). Insects from diverse orders, such as Lepidoptera, Coleoptera, Hemiptera, Diptera, Orthoptera, and Hymenoptera, are susceptible to EPF infection. While some fungi, like those in the Hypocreales family, exhibit broad host ranges, others, such as Entomophthorales, are more host-specific (Roberts and Humber, 1981).

In their natural habitats, EPF act as pathogens, effectively managing insect and mite populations with minimal risk to non-target species. The infection process typically begins with the attachment of fungal spores to the insect's cuticle, followed by germ tube penetration and subsequent colonization of the host's body. EPF spores are often coated with a mucus layer containing proteins and glucans, facilitating adhesion to the insect cuticle and the formation of specialized structures called appressoria. Mechanical pressure and enzymatic activity aid in cuticle penetration, after which the fungus develops vegetatively within the insect's hemocoel (Roberts and Humber, 1981). Insect mortality primarily results from mechanical damage induced by fungal mycelia growth inside the host (mummification) or toxins secreted by the pathogen. Toxins such as destruxin, bavericin, and efrapeptins, produced by fungi like Beauveria, Metarhizium, and Tolypocladium, play crucial roles in the pathogenesis process (Hajek and St. Leger, 1994). Following the insect's demise, the fungus produces hundreds of new spores on the cadaver, initiating a new cycle of infection in subsequent hosts. The efficacy of EPF in targeting specific insect pests can be influenced by various factors, including host plant associations. For instance, research on Beauveria bassiana's pathogenicity to the sweet potato whitefly (*Bemisia tabaci*) revealed significant host plant-dependent effects on mortality rates and conidial production (Santiago-Álvarez et al., 2006).

Biological management of insect pests using EPF presents a desirable and effective alternative to chemical insecticides. Genera such as Beauveria, Metarhizium, Isaria, Lecanicillium, and Hirsutella are utilized as pesticides across agricultural, greenhouse, forest, storage, and residential settings due to their target specificity and broad infectivity range (Sharma and Sharma, 2021).

EPF offers several advantages over chemical insecticides, including their environmentally friendly nature, reduced risk to non-target organisms, and potential for long-term pest management. Additionally, EPF-based pest control strategies can help mitigate the development of insecticide resistance, which is a significant challenge associated with chemical insecticides (Sharma, 2019). One key aspect of utilizing EPF for biological pest management understands its interactions with target insect species and their environments. Research on EPF ecology, including factors influencing their efficacy, host specificity, and persistence in the environment, is crucial for optimizing their use in pest control programs (Roy and Cottrell, 2008).

Furthermore, the development of effective formulations and application strategies is essential for maximizing the efficacy of EPF-based pest management approaches. This includes considerations such as spore viability, adhesion to target insects, and environmental stability (Sharma and Sharma, 2021).

Entomopathogenic Fungi (EPF)

Entomopathogenic fungi (EPF) play diverse and significant roles beyond just insect pest control. They are also involved in biological control strategies targeting plant diseases, rhizosphere colonization, and the promotion of plant growth. Additionally, EPF serve as fungal endophytes, offering multifaceted benefits across agricultural and ecological systems.
In the realm of biological control, EPF act as antagonists against plant diseases, contributing to the management of various pathogens. Through the production of metabolites such as antibiotics, volatile organic compounds, and enzymes, EPF can directly inhibit pathogen growth and reduce their virulence. Mechanisms such as competition, antibiosis, hypovirulence, parasitism, and induced systemic resistance further enhance their efficacy in disease suppression (Ownley and Windham, 2007).

Studies have shown that EPFs like *Beauveria bassiana* and *Lecanicillium spp*. exhibit antagonistic activity not only against insects but also against plant pathogens (Kim et al., 2008). The antagonistic mechanisms employed by EPF, including antibiosis, competition, and induced systemic resistance, contribute to their efficacy in suppressing plant diseases caused by various pathogens (Benhamou and Brodeur, 2001).

Furthermore, EPF-based fungal infections have emerged as effective, cost-efficient, and environmentally friendly strategies for controlling insect pests (Wraight et al., 2001). Their multifunctional characteristics make EPF valuable components of integrated pest management (IPM) programs, where they can contribute to pest control while also offering benefits such as disease suppression, rhizosphere colonization, and plant growth promotion.

Entomopathogenic nematodes (EPNs) represent a diverse group of roundworms that play crucial roles in biological pest management. These soft-bodied parasites, typically around 0.5 mm in length, have been identified across 23 families of worms (Koppenhöfer, 2007). In agricultural pest management, EPNs from families such as Heterorhabditidae and Steinernematidae have been effectively utilized as biological insecticides (Koppenhöfer, 2007).

Entomopathogenic Nematodes (EPNs)

EPNs naturally inhabit soil environments and employ chemical signals, including carbon dioxide, to locate their insect hosts (Kaya and Gaugler, 1993). Commercially produced EPNs are widely used as biological control agents against various soil-dwelling insect pests due to their symbiotic relationship with bacteria that aids in insect pest management (Boemare, 2002).

The interaction between EPNs and their symbiotic bacteria enables them to parasitize and kill insect pests efficiently. Infectious juveniles of EPNs enter the insect host's body and release symbiotic bacteria, inducing septicemia and ultimately killing the host within 24–48 hours (Poinar, 1990). The bacteria proliferate rapidly, providing food for the nematodes as they consume the insect's tissues. Subsequently, the nematodes complete several generations within the insect cadaver, further enhancing their reproductive success (Bedding and Molyneux, 1982).

EPNs are mass-produced using various methods, including in vivo and in vitro techniques, to meet commercial demand (Shapiro-Ilan and Gaugler, 2012). Different host organisms, such as wax moth larvae, are utilized to rear nematodes, and liquid fermentation processes are employed for large-scale production (Friedman, 1990).

EPNs have demonstrated efficacy against a wide range of pest insects, including those belonging to the orders Coleoptera, Lepidoptera, and Diptera (Garcia et al., 2005; 2013). Studies have shown that these nematodes remain unaffected by certain pesticides, making them valuable components of integrated pest management strategies (Garcia et al., 2013). Additionally, the application of certain beneficial bacteria, such as Pseudomonas fluorescens, has been found to enhance crop production while inhibiting nematode survival in soil (Shamseldin et al., 2010).

In conclusion, entomopathogenic nematodes offer a promising and environmentally friendly approach to pest management in agriculture. Their ability to parasitize and kill insect pests, combined with their symbiotic relationship with bacteria, makes them valuable assets in integrated pest management programs aimed at promoting sustainable agriculture.

Furthermore, the effectiveness of EPNs against various insect pests has been extensively researched, leading to a better understanding of their potential applications in pest control. Studies have evaluated the pathogenicity of different EPN strains against specific target pests and assessed their performance under different environmental conditions.

For example, research conducted by Garcia et al. (2005) tested the efficacy of different EPN strains against Capnodis tenebrionis larvae, demonstrating varying levels of mortality depending on the nematode species and concentration used. Similarly, Garcia et al. (2013) investigated the impact of three native EPN species on Tuta absoluta larvae, pupae, and adults, highlighting the effectiveness of these nematodes in controlling the pest at different life stages.

Moreover, studies have examined the compatibility of EPNs with other pest management strategies, such as chemical pesticides and beneficial microbes. Garcia et al. (2013) found that EPNs were not adversely affected by commonly used pesticides against *T. absoluta*, suggesting their potential for integration into existing pest management programs without interference from chemical treatments.

Additionally, research by Shamseldin et al. (2010) demonstrated the dual benefits of inoculating crops with beneficial bacteria like Pseudomonas fluorescens, which not only improved crop productivity and fruit quality but also suppressed nematode populations in the soil, further enhancing the effectiveness of EPNs in pest control.

Overall, the continued investigation into the biology, ecology, and practical applications of entomopathogenic nematodes holds promise for the development of sustainable pest management strategies in agriculture. By harnessing the synergistic interactions between EPNs, symbiotic bacteria, and other beneficial microbes, researchers can contribute to the advancement of integrated pest management approaches that are effective, environmentally friendly, and economically viable.

Moreover, EPNs exhibit diverse characteristics that contribute to their effectiveness as biological control agents. These nematodes thrive in a wide range of environmental conditions, although they are particularly suited to sandy soils with a pH range of 4–8 (Grewal and Peters, 2005). However, they are susceptible to extremes of temperature, dehydration, and UV radiation, highlighting the importance of understanding their ecological requirements for successful application in pest management programs.

Research conducted between 1990 and 2010 in various regions of Italy identified *Steinernema feltiae* and *Heterorhabditis bacteriophora* as the predominant species of EPNs, underscoring their prevalence and potential for use in pest control strategies (Tarasco et al., 2015). Similarly, studies evaluating the efficacy of different EPN strains against pest insects like *Capnodis tenebrionis* larvae and *Tuta absoluta* have demonstrated significant levels of pathogenicity and mortality, highlighting the utility of EPNs as effective biocontrol agents (Garcia et al., 2005; 2013).

Furthermore, investigations into the impact of commonly used pesticides on EPNs have revealed their resilience to chemical treatments, reaffirming their viability as sustainable alternatives to conventional insecticides (Garcia et al., 2013). Additionally, the application of beneficial bacteria, such as *Pseudomonas fluorescens*, has shown promise in enhancing crop productivity while simultaneously suppressing nematode populations in soil, further emphasizing the potential of integrated pest management approaches (Shamseldin et al., 2010).

Entomopathogenic Viruses (EPVs)

Entomopathogenic viruses (EPVs) have emerged as potent tools in the field of insect pest management, offering a promising alternative to conventional chemical insecticides. While viruses were initially explored for pest control in the early 1900s, the first virus-based insecticide was registered in the USA in 1970, marking a significant milestone in the use of viral agents for pest management (Ignoffo, 1973). Since then, several viruses have been identified and approved for use in controlling insect pests, with ongoing research aimed at characterizing and evaluating new viral strains (López-Ferber, 2020).

EPVs target a wide range of insect species and can be utilized effectively as biological control agents due to their specificity and ability to infect and kill pest insects. These viruses can possess various genetic compositions, including double-stranded DNA (dsDNA), single-stranded DNA (ssDNA), double-stranded RNA (dsRNA), and single-stranded RNA (ssRNA), with each type exhibiting unique characteristics and mechanisms of action (van Regenmortel et al., 2000).

The International Committee on Taxonomy of Viruses (ICTV) categorizes EPVs into 12 viral families, each with specific host ranges and pathogenicities (van Regenmortel et al., 2000). Three families, namely Baculoviridae, Polydnaviridae, and Ascoviridae, are particularly noteworthy for their host specificity and non-pathogenicity to beneficial insects and other non-target organisms (van Regenmortel et al., 2000). Baculoviruses, for example, have long been recognized as environmentally benign alternatives to chemical pesticides due to their narrow host range and harmless nature to mammals (Granados and Williams, 1986).

Baculoviruses, which are commonly used in pest management, exhibit distinctive infection patterns and symptoms in their host insects. Infected insects typically exhibit reduced activity, cessation of feeding, and cessation of growth as initial symptoms, followed by systemic infection and eventual host death (Granados and Williams, 1986). Baculovirus-infected larvae often display a whitish appearance due to infection of the fat body, leading to a translucent exoskeleton that eventually ruptures, releasing billions of occlusion bodies (OBs) into the environment, aiding in viral spread (Granados and Williams, 1986).

Research into EPVs has led to the identification of various viral strains with specific characteristics and modes of action against target insect pests. For example, studies on nuclear polyhedrosis virus isolates from the beet armyworm (*Spodoptera exigua*) have revealed distinct genotypes and differing virulence levels, highlighting the genetic diversity and potential applications of EPVs in pest management (Caballero et al., 1992).

EPVs have shown promise in controlling a range of pest insects, including cotton pests like *S. exigua* and *Pectinophora gossypiella*, contributing to effective pest management strategies in agriculture (Caballero et al., 1992). With their limited host range and low risk to non-target organisms, EPVs offer a safe and environmentally friendly approach to pest control, making them valuable assets in integrated pest management programs.

Entomopathogenic Bacteria

Entomopathogenic bacteria offer a promising avenue for biological pest control, boasting several advantages over chemical pesticides. Their mode of action is often more intricate, targeting a range of sites where resistant pests are likely to emerge, making them a safer and more sustainable option (Ruiu, 2015). While entomopathic bacteria can be used independently, they are most effective when integrated with insecticides, either in rotation or in combination, to maximize efficacy and environmental sustainability (Musser et al., 2006).

Bacterial entomopathogens, such as those belonging to families like Bacillaceae, Pseudomonadaceae, Enterobacteriaceae, Streptococcaceae, and Micrococcaceae, are known for their ability to infect and control insect pests. *Bacillus thuringiensis* (Bt), a common entomopathogenic bacterium, is widely used to control caterpillars and beetles by producing spores containing insecticidal endotoxins known as Cry proteins (Pigott and Ellar, 2007). These toxins act through ingestion, targeting the insect gut epithelium and leading to its destruction. Bt toxins have been extensively studied for their impact on both target and non-target species, with generally low direct effects observed on non-target organisms (Marchetti et al., 2012). The application of Bt bioinsecticides in agro-ecosystems and other environments typically results in the rapid death of target insects without significant spore buildup in the environment (Ignoffo, 1992). Furthermore, Bt crops, genetically modified to express Bt-endotoxin genes, have been shown to reduce the use of conventional pesticides significantly, offering effective pest control while minimizing environmental impact (Ruiu, 2015).

However, the introduction of genetically modified (GM) crops expressing insecticidal endotoxins has raised concerns about secondary pest outbreaks, as seen with mirid bugs in Bt cotton cultivated in China (Ruiu, 2015). Despite these challenges, GM crops have revolutionized farming in many countries and continue to be an essential tool in pest management strategies.

Conclusion

In conclusion, entomopathogens, including fungi, nematodes, viruses, and bacteria, offer sustainable alternatives to chemical insecticides for agricultural pest management. These organisms demonstrate diverse mechanisms of action, target specificity, and environmental safety, making them valuable components of integrated pest management strategies. Continued research and development in this field hold promise for effective, environmentally friendly, and economically viable pest control solutions in agriculture. Furthermore, the efficacy of entomopathogens such as fungi, nematodes, viruses, and bacteria extends beyond insect pest control to include disease suppression and the promotion of plant growth. Their multifunctional roles underscore their potential for fostering sustainable agricultural practices. With ongoing advancements in understanding their biology, ecology, and practical applications, entomopathogens are poised to play a pivotal role in shaping the future of pest management, ensuring food security, environmental conservation, and economic viability in agriculture.

List of Abbreviations

BCAs: Biological control agents; EPF: Enteropathogenic fungi; EPNs: Entomopathogenicnematode; ICTV: International Committee on Taxonomy of Viruses; dsDNA: double-stranded DNA; ssDNA: single-stranded DNA; GV: Granulovirus; NPV: Nucleopolyhedrovirus; OBs: Occlusion bodies; Bt: Bacillusthuringiensis; GV: Granulovirus; EPV:Entomopathogenicviruses

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