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Endophytic fungi and insect predators: Synergistic biocontrol plant pest and diseases

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Abstract
In the pursuit of sustainable agricultural practices, the use of biological control agents has emerged as a viable alternative to synthetic chemicals for managing plant pests and diseases. Among these, endophytic fungi and insect predators represent two ecologically compatible and effective components of integrated pest management (IPM). Endophytic fungi live within plant tissues without causing disease and offer benefits such as growth promotion, disease suppression and enhanced resistance to biotic stress. Insect predators, on the other hand, play a crucial role in directly controlling pest populations. This article explores the synergistic potential of combining endophytic fungi and insect predators to achieve holistic pest and disease management. It discusses the mechanisms of action, compatibility, field applications, benefits, challenges and future directions, offering a comprehensive overview of how this dual biocontrol strategy can revolutionize pest management in modern agriculture.

Keywords: Endophytic fungi, insect predators, biocontrol, integrated pest management, sustainable agriculture, pest suppression, microbial interactions

Introduction
Agricultural productivity is increasingly threatened by plant pests and diseases, exacerbated by climate change, monoculture practices and pesticide resistance [7, 70]. Traditional pest control methods have relied heavily on chemical pesticides, which can lead to environmental degradation, non-target effects and resistance development [18, 148]. As a result, there is growing interest in sustainable pest control strategies that utilize biological organisms to maintain ecological balance and crop health [29, 127]. Endophytic fungi and insect predators are two biocontrol agents with proven potential. While endophytic fungi confer systemic resistance and antagonism against pathogens, insect predators reduce pest populations through direct predation [92]. The integration of these two biological entities offers a promising synergistic approach to pest and disease management [107]. This article examines the science and application of endophytic fungi and insect predators as synergistic agents in biocontrol.

The concept of biological control has evolved significantly over the past century. The first notable success was the introduction of the vedalia beetle (*Rodolia cardinalis*) from Australia to California in the late 1800s by Charles Valentine Riley to control cottony cushion scale (*Icerya purchasi*), a pest threatening citrus orchards [69, 128]. This event marked the beginning of classical biological control and demonstrated the potential of using natural enemies in pest management [91]. The role of fungi in plant health also gained attention in the early 20th century, with mycologists such as H.W [108]. Whetzel and Charles Drechsler studying fungal pathogens and beneficial fungi. In the 1960s and 1970s, research into entomo-pathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* gained momentum for their insecticidal properties. More recently, the exploration of endophytic fungi as internal colonizers providing systemic protection against pests and pathogens has opened new avenues [109]. Scientists like Dr. Fernando E [19, 90]. Vega have significantly advanced the understanding of fungal endophytes as entomo-pathogens and plant symbionts. Parallel advancements in conservation biological control, championed by entomologists such as Paul DeBach and R.L. Luck, emphasized habitat management to support natural predators [8]. These historical milestones laid the groundwork for today's integrated pest management strategies that harness both microbial and insect-based control measures [110, 149]. By building upon these historical advances, researchers are now exploring the synergistic potential of combining endophytic fungi and insect predators to create robust, ecologically sound pest management systems [111, 129].

Endophytic Fungi

Endophytic Fungi Biology and Biocontrol Potential Endophytic fungi are microorganisms that colonize the internal tissues of plants without causing visible symptoms of disease. They establish symbiotic relationships with host plants, often providing benefits such as improved growth, enhanced stress tolerance and disease resistance [29, 71]. These fungi can be isolated from virtually all plant species and are particularly abundant in grasses, legumes and woody plants. Their presence in various plant parts, roots, stems, leaves and seeds indicates a widespread and often systemic colonization pattern [1, 130]. Botanically, endophytic fungi interact with the plant vascular system and intercellular spaces, forming structures such as hyphal networks, micro-sclerotia and conidiophores [68, 93]. These interactions are largely governed by molecular signalling between the host plant and the fungal symbiont [112]. For example, in mutualistic relationships, the plant may provide carbohydrates to the fungus, which in turn secretes secondary metabolites with antimicrobial, insecticidal, or growth-promoting properties [48].

One widely studied example is the association between Neotyphodium endophytes and cool-season grasses like tall fescue (*Festuca arundinacea*) and perennial ryegrass (*Lolium perenne*) [67, 113]. These endophytes enhance plant tolerance to herbivory and drought by producing alkaloids such as peramine and lolitrem [131]. Another example is *Trichoderma harzianum*, a root-colonizing endophyte that has demonstrated significant biocontrol activity against soilborne pathogens like Fusarium and Rhizoctonia [94, 150]. Endophytic fungi also play a role in enhancing plant immunity through induced systemic resistance (ISR). By triggering host defense pathways, these fungi help the plant to better withstand pest and pathogen attacks. They are also involved in nutrient cycling, promoting phosphorus solubilisation and nitrogen fixation through interactions with other microbial communities [20, 30].

Several scientists have contributed to the foundational understanding of endophytic fungi. Dr. Gary Strobel from Montana State University was among the pioneers in exploring endophytic fungi from rainforest plants, leading to the discovery of novel bioactive compounds with pharmaceutical and agricultural potential [9, 66]. Dr. Maria Helena Pereira da Silva and her colleagues have studied the biodiversity and endophytic roles of fungi in tropical and subtropical ecosystems, revealing the ecological importance of these organisms [72, 151]. Dr. Fernando Vega's research has expanded the understanding of fungal endophytes with entomo-pathogenic properties, bridging the fields of mycology and entomology [47, 132]. The biocontrol potential of endophytic fungi arises from several mechanisms:

- Production of antimicrobial and insecticidal metabolites (e.g., beauvericin, gliotoxin) Endophytic fungi produce a variety of secondary metabolites with strong antimicrobial and insecticidal properties [95, 114]. Compounds like beauvericin and gliotoxin disrupt cellular membranes, inhibit vital enzymes and induce oxidative stress in pathogens and insect pests. These metabolites act as chemical defenses that protect the host plant from a broad range of biological threats, enhancing its resistance without reliance on synthetic chemicals [31, 152].
- Competition with pathogens for nutrients and space One of the foundational mechanisms of biocontrol involves resource competition [2, 133]. Endophytic fungi colonize internal plant tissues, effectively occupying the ecological niches that might otherwise be exploited by pathogens [96]. By rapidly utilizing available nutrients and physically blocking pathogen access to infection sites, these fungi outcompete disease-causing organisms, reducing infection rates and pathogen proliferation [65].
- Enzyme-mediated degradation of pathogen cell walls (e.g., chitinases, glucanases) Endophytes also produce hydrolytic enzymes, such as chitinases and β-1, 3-glucanases, which break down the structural components of pathogen cell walls [32, 64]. These enzymes target key polysaccharides like chitin and glucans, compromising cell wall integrity and leading to lysis of the pathogen [73, 89]. This enzymatic action is particularly effective against fungal pathogens and is a crucial part of the direct antagonistic defense strategy [10, 49].
- Modulation of plant defense hormones like jasmonic acid and salicylic acid Endophytic fungi influence the host plant's immune system by modulating key signalling pathways. They can enhance systemic acquired resistance (SAR) and induced systemic resistance (ISR) by altering the biosynthesis and signalling of plant defense hormones such as jasmonic acid and salicylic acid [74, 115]. This hormonal priming leads to faster and stronger defensive responses upon pathogen or insect attack, allowing plants to resist stress more effectively and recover more rapidly [21, 134].

In agricultural systems, endophytic fungi are increasingly being utilized for seed treatments, root inoculants and foliar sprays to reduce reliance on chemical pesticides and promote crop resilience [135]. Their multifaceted roles make them key players in the development of sustainable, biologically intensive cropping systems [63, 153]. Common genera of endophytic fungi with biocontrol potential include Trichoderma, Beauveria, Fusarium (non-pathogenic strains) and Cladosporium. Trichoderma species, for example, are well-known for their ability to produce enzymes and secondary metabolites that inhibit phyto-pathogens [46, 154].

Insect Predators in Pest Management

Insect Predators in Pest Management Insect predators are natural enemies that feed on pest insects, playing a crucial role in reducing their populations and preventing crop damage [117]. These beneficial organisms include various groups such as lady beetles (Coccinellidae), green lacewings (Chrysopidae), predatory bugs like assassin bugs (Reduviidae) and parasitoid wasps (Ichneumonidae and Braconidae) [97, 116]. Predators are often generalists, meaning they can target a broad range of pest species including aphids, whiteflies, thrips, mites and caterpillars. Their effectiveness in pest suppression makes them essential components of integrated pest management (IPM) programs [11, 33]. The advantages of utilizing insect predators extend beyond direct pest control. They contribute to a reduction in pest outbreaks, minimize the environmental impact associated with synthetic pesticides and are usually compatible with other biological control agents such as endophytic fungi or microbial pesticides [62, 136]. Furthermore, they help preserve on-farm biodiversity and ecological resilience. Field application strategies include augmentation, where mass-reared predators are released periodically to control specific pest populations and conservation, which involves creating favourable habitats, such as hedgerows, flowering strips, or reduced pesticide zones, to enhance the survival and efficacy of naturally occurring predator populations [45, 98]. The success of these strategies depends on various ecological factors, including habitat structure, climate, availability of prey and absence of harmful chemical residues [137]. Understanding the biology and behaviour of these predators is essential to optimize their deployment in diverse cropping systems [22, 44, 75].

Table 1: Common Insect Predators and Their Target Pests

Predator Name	Common Name	Target Pests	Notable Features
Coccinella septempunctata	Seven-spotted lady beetle	Aphids, mealybugs	Rapid reproduction; voracious feeder
Chrysoperla carnea	Green lacewing	Aphids, thrips, whiteflies	Larvae are effective hunters
Orius insidiosus	Minute pirate bug	Thrips, mites, aphids	Small, agile, highly effective in greenhouses
Harmonia axyridis	Asian lady beetle	Aphids, scales, caterpillars	Broad pest range, but invasive in some areas
Podisus maculiventris	Spined soldier bug	Caterpillars, beetle larvae	Strong predatory capacity on larger pests
Trichogramma spp.	Parasitic wasps	Lepidopteran eggs	Egg parasitoids, widely used in IPM

Synergistic Interactions between Endophytic Fungi and Insect Predators

Synergistic Interactions between Endophytic Fungi and Insect Predators The combined use of endophytic fungi and insect predators can lead to synergistic effects, where the interaction between the two agents enhances overall pest suppression beyond what is achieved by each agent alone [2, 12, 117]. This synergy arises from the complementary mechanisms of action and mutual reinforcement of plant defense systems [35, 50]. Such integrated biocontrol approaches contribute to robust pest resistance, ecological balance and reduced pesticide dependence [61, 76]. The following are ten key aspects illustrating these synergistic interactions:

1. **Enhanced Attraction of Predators via Volatile Organic Compounds (VOCs):** Endophytic fungi like *Beauveria bassiana* can modulate the volatile profile of plants, inducing the release of VOCs that attract insect predators such as *Chrysoperla carnea* and lady beetles. These volatiles act as cues, guiding predators to pest-infested areas, thus amplifying pest suppression [77, 138].
2. **Increased Pest Susceptibility to Predation:** Pests feeding on endophyte-inoculated plants often suffer reduced growth, feeding efficiency, or reproductive capacity. This compromised fitness makes them easier targets for insect predators, leading to a higher predation rate [51, 88].
3. **Internal and External Plant Protection:** Endophytic fungi provide internal systemic protection by colonizing plant tissues and producing bioactive compounds. Insect predators patrol the plant surface, offering external protection. This dual-layered defense reduces pest establishment and damage [23, 43].
4. **Reduction in Pest Reinfestation:** Endophytic colonization limits pest development within the plant, while predators eliminate mobile pests. This reduces the likelihood of re-infestation and pest population recovery, offering long-term control [99].
5. **Improved Plant Health and Vigour:** The stress-mitigating effects of endophytes, coupled with the reduction of pest pressure by predators, result in healthier plants with better physiological performance. Vigorous plants are more resistant to pest outbreaks and can better support beneficial organisms [78, 118].
6. **Habitat Modification and Predator Retention:** Endophytic fungi can indirectly modify plant traits, such as increased trichome density or altered surface chemistry, which may provide better microhabitats or hunting grounds for predators, thereby improving their persistence in crop fields [36, 139].
7. **Induced Systemic Resistance (ISR) and Enhanced Predator Activity:** Endophytes trigger ISR in plants by activating signalling pathways such as jasmonic acid and salicylic acid. This primed state improves the plant's defensive capacity and can increase nectar production or other cues that benefit predatory insects [79].
8. **Complementary Pest Suppression Spectrum:** Fungal endophytes and insect predators often target different stages or species of pests. While fungi may target soil-dwelling or internal pests, predators are effective against surface-feeding pests. This complementary action enhances overall pest control [60, 119].
9. **Mitigation of Pest Resistance Development:** The use of multiple control agents with distinct modes of action reduces the selective pressure on pests, delaying the development of resistance. This integrated approach enhances the sustainability of biocontrol strategies [13, 80].
10. **Compatibility with Ecological Farming Practices:** Both endophytic fungi and insect predators are compatible with organic and ecological farming systems. Their integration supports biodiversity, ecological services and resilience in agroecosystems, aligning with sustainable agriculture goals [24, 42].

Compatibility and Co-application

Compatibility and Co-application Strategies For effective synergistic biocontrol, ensuring the compatibility of endophytic fungi and insect predators is essential to avoid antagonistic effects that could reduce overall efficacy [25, 52]. Compatibility is influenced by multiple factors, including the non-toxicity of fungal secondary metabolites to the insect predators, the persistence and colonization efficiency of the fungi within plant tissues and the behavioural and ecological interactions between the two agents. Some fungal strains produce compounds that may harm beneficial insects, making careful selection of fungal species and isolates crucial [37, 81, 120]. Additionally, ecological factors such as habitat overlap, diurnal activity patterns and prey-predator dynamics can influence their co-functionality [140]. Co-application strategies aim to harmonize the strengths of both biocontrol agents through methods such as sequential or simultaneous application, depending on the crop cycle and pest infestation stage [100]. Selecting compatible combinations, for example, pairing *Beauveria bassiana* with *Chrysoperla carnea* has shown promise in multiple studies [4, 59]. Moreover, enhancing predator establishment through the use of floral strips, banker plants, or synthetic attractants can further improve efficacy [82]. Habitat manipulation not only supports predator longevity and reproduction but may also enhance fungal persistence by maintaining suitable microclimatic conditions. An integrated strategy that combines biological insights, ecological management and precision delivery methods is crucial to successfully deploying these biocontrol agents in tandem [53, 141]. Field Applications and Case Studies Several case studies demonstrate the practical benefits of integrating endophytic fungi and insect predators in pest management programs. The following table outlines key examples from various cropping systems, highlighting the fungal species used, corresponding insect predators, targeted pests and observed outcomes [14, 121].

Crop Type	Endophytic Fungus	Insect Predator	Target Pest(s)	Observed Outcome
Tomato	*Trichoderma harzianum*	*Phytoseiulus persimilis*	Spider mites, soil-borne pathogens	Significant reduction in pest pressure and disease incidence
Cotton	*Beauveria bassiana*	Coccinellid beetles (ladybugs)	Aphids	Reduced aphid fitness, enhanced predation, increased yield
Cabbage	*Metarhizium anisopliae*	Parasitoid wasps	Lepidopteran larvae	Decreased larval survival, increased parasitoid success
Maize	*Fusarium oxysporum* (non-pathogenic)	*Chrysoperla carnea*	Corn borers, aphids	Improved plant growth, reduced pest populations
Soybean	*Trichoderma viride*	*Orius insidiosus*	Whiteflies, thrips	Dual suppression of pests, improved pod set
Rice	*Beauveria bassiana*	Spiders, ground beetles	Stem borers, plant hoppers	Enhanced predator activity, reduced pest density
Eggplant	*Clonostachys rosea*	Green lacewings	Whiteflies, aphids	Improved pest control and plant vigour
Chili	*Metarhizium anisopliae*	Syrphid fly larvae	Aphids	Decreased pest load and pesticide application
Grapevine	*Acremonium strictum*	Ladybird beetles	Mealybugs	Suppression of pest population and increased fruit set
Strawberry	*Trichoderma atroviride*	Predatory mites and minute pirate bugs	Spider mites, thrips	Enhanced biological control, reduced need for chemical interventions

Benefits of Synergistic Biocontrol

1. **Reduced Dependence on Synthetic Pesticides:** The integration of endophytic fungi and insect predators significantly minimizes the need for chemical pesticides [142]. This shift not only lowers input costs for farmers but also reduces environmental contamination, residue accumulation in food and pesticide-related health risks [38, 83].
2. **Broad-Spectrum Pest and Disease Control:** Synergistic biocontrol agents collectively target a wide range of pests and pathogens. While endophytic fungi suppress soil-borne and internal plant pathogens, insect predators manage external pests, resulting in comprehensive crop protection [15, 101].
3. **Lower Risk of Resistance Development:** Using multiple biological agents with different mechanisms of action reduces the evolutionary pressure on pests to develop resistance [58]. This integrated approach ensures long-term effectiveness compared to single-method control strategies [26, 122].
4. **Enhanced Plant Growth and Yield:** Endophytic fungi improve nutrient uptake and stress resilience, while predator-induced pest suppression prevents damage to plant tissues [143]. Together, they contribute to better plant vigour, leading to higher crop yields and better quality produce [54].
5. **Improved Ecological Sustainability:** Biocontrol methods support ecological balance by preserving beneficial organisms, enhancing soil health and reducing chemical footprints. This aligns with agro-ecological principles and promotes sustainability in agricultural landscapes [39, 123].
6. **Support for Pollinator and Natural Enemy Populations:** Unlike broad-spectrum insecticides, biocontrol agents do not harm non-target organisms such as pollinators or other natural enemies [57]. Their use helps conserve beneficial insect populations, which are essential for crop pollination and natural pest suppression [84].
7. **Resilience against Climate Stressors:** Endophytic fungi often enhance tolerance to abiotic stressors like drought, salinity and extreme temperatures [144]. This resilience, coupled with reduced pest stress from predator activity, helps crops better withstand changing climatic conditions [55, 124].
8. **Long-Term Soil Health Improvement:** The use of non-chemical control methods fosters beneficial soil microbial communities. Endophytes and predator-friendly practices reduce soil degradation and enhance microbial diversity, which is crucial for long-term soil productivity [5, 16].
9. **Economic Viability for Farmers:** Though initial implementation may require training or investment in biocontrol agents, the long-term cost savings from reduced chemical use, improved yields and fewer pest outbreaks make synergistic biocontrol economically attractive to farmers [102].
10. **Compatibility with Organic and Low-Input Farming Systems:** Endophytic fungi and insect predators are compatible with organic farming regulations and low-input systems. Their adoption supports certification

requirements and aligns with consumer demand for residue-free, environmentally responsible produce [85].

Challenges and Limitations

- **Inconsistent field performance due to Environmental Variability:** The effectiveness of endophytic fungi and insect predators can be highly dependent on environmental conditions such as temperature, humidity and soil characteristics [145]. Fluctuating field conditions may hinder fungal colonization, predator activity, or both, leading to inconsistent biocontrol outcomes [27].
- **Limited understanding of Complex Interactions:** The ecological and molecular interactions between endophytes, insect predators, host plants and pest species are still not fully understood. This knowledge gap can complicate the prediction of biocontrol outcomes and hinder the development of effective, science-based application protocols [40, 125].
- **Potential Antagonism between Biocontrol Agents:** Although intended to act synergistically, certain combinations of fungi and insect predators may exhibit antagonistic interactions [146]. For example, fungal metabolites might negatively affect predator health or behaviour. Ensuring compatibility requires extensive screening and tailored selection of agent combinations [86].
- **Regulatory Hurdles and Lack of Commercial Formulations:** The registration and approval processes for biocontrol agents are often complex, time-consuming and costly. In many regions, there are limited commercial formulations that integrate both endophytes and predators, which restricts market availability and farmer adoption [103].
- **Farmer Awareness and Technical Training Gaps:** The successful use of synergistic biocontrol relies on farmers' knowledge of agent selection, timing and application techniques. Inadequate awareness, training and extension support can lead to improper usage and reduced efficacy in the field [105].
- **Short Shelf Life and Storage Constraints:** Biological agents often require specific storage conditions to maintain viability. Endophytic fungi may have limited shelf lives, while insect predators may need live transport and release, posing logistical and cost-related challenges for widespread distribution [17, 126].
- **Compatibility with Existing Farming Practices:** Integrating synergistic biocontrol with existing agronomic practices such as tillage, irrigation, or pesticide use can be difficult [56, 147]. Some conventional practices may disrupt predator habitats or fungal colonization, requiring adjustments and system redesign [41, 87].
- **Scalability and Cost of Mass Production:** Producing high-quality, cost-effective formulations of both endophytic fungi and insect predators at a commercial scale remains challenging [18, 28]. Technical constraints in formulation technology and rearing systems can limit the scalability of this biocontrol approach [6, 106].

Conclusion

The synergistic use of endophytic fungi and insect predators represents a transformative and ecologically sound approach to managing plant pests and diseases. This dual strategy leverages the internal colonization abilities of endophytic fungi and the external pest suppression capabilities of insect predators, providing a multifaceted line of defense for crops. Endophytic fungi such as *Beauveria bassiana*, Trichoderma spp. and *Metarhizium anisopliae* colonize plant tissues and confer a range of benefits, including enhanced plant immunity, improved nutrient acquisition and resistance against various pathogens. Insect predators, including ladybird beetles, lacewings, parasitoid wasps and predatory mites, provide top-down control of key insect pests like aphids, whiteflies, thrips and caterpillars. Together, these biological control agents offer broad-spectrum protection, targeting multiple pest and disease threats simultaneously. Their mechanisms of action complement each other while endophytes work internally to suppress pathogens and weaken pests, insect predators act externally to directly reduce pest populations. Furthermore, endophytic fungi can induce changes in plant volatiles, attracting natural enemies and thereby reinforcing predator effectiveness. This synergy not only improves pest suppression outcomes but also enhances the stability and resilience of agroecosystems. Beyond pest management, the synergistic application of endophytic fungi and insect predators contributes to overall crop health and productivity. Plants colonized by endophytes often show improved growth, increased tolerance to abiotic stress and better yield performance. Predator-based pest reduction minimizes tissue damage, preserving photosynthetic efficiency and physiological function. Additionally, reducing reliance on synthetic pesticides helps mitigate risks associated with pesticide resistance, environmental pollution and non-target organism harm, including pollinators and beneficial insects. Despite the clear benefits, widespread adoption faces several challenges. The success of this biocontrol strategy depends on selecting compatible species, understanding their interactions and adapting application protocols to specific agro-ecological contexts. Issues such as inconsistent field performance, limited commercial availability, potential antagonism between agents and knowledge gaps in agent ecology must be addressed. Bridging these gaps calls for interdisciplinary research that integrates plant pathology, entomology, microbial ecology and agronomy. Developing standardized, farmer-friendly formulations and delivery systems will also be critical.

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