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Manifestation of Endophytes in Pest management: Their existence and mechanism of action

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Abstract

Endophytes are the microorganisms intricately associated with the plant tissues without causing disease and accelerate the plant growth and development by playing a pivotal role in enhancing plant resilience. Among their many functions, entomopathogenic endophytes have emerged as promising allies in sustainable pest management, producing metabolites and enzymes that deter or kill insect herbivores. They also contribute to plant growth by facilitating nutrient uptake, regulating hormones, and improving stress tolerance. This review highlights the dual role of fungal and bacterial endophytes as growth promoters and natural biocontrol agents, with special emphasis on their mechanisms of action and potential to reduce reliance on chemical pesticides. The future application of endophytes in agriculture, biotechnology, and pharmaceuticals presents new opportunities for environmentally friendly crop protection and improved productivity.

Keywords: *Endophytes, metabolites, tolerance, biocontrol, productivity.*

Introduction

Endophytes are microorganisms that inhabit internal plant tissues without causing apparent disease symptoms, and they are increasingly recognized as vital partners in plant ecosystems. Residing in roots, stems, and leaves, these microbes have co-evolved with land plants and developed functional strategies that allow mutual survival, including nutrient exchange and enhanced host fitness (1) (2). Their ability to persist within the plant body, despite chemical and physical defense barriers, reflects sophisticated adaptations that secure their ecological niche (3). Early studies described endophytes as cryptic colonizers of great interest because of their capacity to inhabit plant tissues without triggering visible disease (4). Subsequent research revealed that they comprise phylogenetically diverse microbial groups and engage in complex interactions within the endosphere and rhizosphere (5) (6). Beyond their ecological role, endophytes have been shown to enhance crop productivity, disease resistance, and tolerance to environmental stressors, thereby improving yield stability (7). Their functional versatility includes the production of bioactive metabolites (8) promotion of nutrient acquisition (9), and modulation of plant responses to stress. Endophytic microorganisms not only strengthen plant growth and resilience but also act as a hidden layer of defense against biotic stresses (10) (11). Many of their bioactive compounds, originally linked to disease resistance or stress tolerance, are now recognized to influence herbivorous insects as well (12). This dual function has drawn attention to their role as entomopathogens, offering a natural and environmentally compatible approach to pest suppression. Thus, endophytes emerge not only as plant growth promoters but also as promising allies in integrated pest management. The plentitude of pest dynamics can inflict substantial losses, with global yield reductions estimated at around 15 % in major crops (13). Managing these pests once they exceed the economic threshold requires approaches that are both effective and environmentally sound. In this context, endophytic microorganisms are gaining attention by offering protection through the production of secondary metabolites, direct entomopathogenic activity, and other modes of action. This review comprises current understanding of such interactions, emphasizing their potential applications in sustainable crop protection.

Growth-promoting factors released by endophytes

Endophytic microorganisms are increasingly recognized not only for their defensive role against pests and pathogens but also for their capacity to enhance plant growth and vigor (Fig. 1). These benefits arise through multiple mechanisms, including nutrient mobilization, modulation of plant hormones, and improvement of stress tolerance, siderophore production, osmolyte production and carbon modulation etc.

Nutrient Acquisition and Mobilization

Biological Nitrogen Fixation: Diverse genera such as *Bacillus, Pseudomonas, Rhizobium, Fusarium*, and *Klebsiella* have been documented in both leguminous and non-leguminous hosts, where they support nitrogen assimilation (14).

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This capacity is underpinned by the enzyme nitrogenase, which facilitates the conversion of atmospheric nitrogen into plant-available forms. The activity of nitrogenase has been experimentally demonstrated in several endophytic strains through acetylene reduction assays (15). Many endophytic bacteria release organic acids and enzymes that transform insoluble phosphorus into bioavailable forms (16). For example, in wheat ecosystems, both endophytic and bacterial populations of rhizosphere have been shown to enhance phosphorus solubilization efficiency under nutrient-deficient conditions (17).

Phytohormone Modulation

Beyond mineral nutrition, endophytes significantly influence plant development by modulating phytohormone dynamics. They are known to synthesize phytohormones such as indole-3-acetic acid (IAA), gibberellins, cytokinins, and ethylene modulators, including 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase. Together, these molecules stimulate root and shoot development, alleviate abiotic stress, and even facilitate beneficial associations such as mycorrhization (18). The production of growth regulators allows endophytes to orchestrate complex physiological changes in their hosts (19) (20).

Siderophore Production & Iron Acquisition

Endophytes often produce siderophores, which are small, high-affinity iron-chelating compounds. In soil and plant tissues, iron is mostly present in an insoluble form (Fe^{3+}) that plants cannot absorb. Bacterial and fungal siderophores solubilize this iron, forming a complex that can be recognized and taken up by the plant. This directly improves the plant's iron nutrition, which is vital for chlorophyll synthesis and electron transport in photosynthesis. Additionally, by sequestering all available iron, endophytes can starve and inhibit the growth of pathogenic microbes in the plant's immediate environment, a form of biological control (21).

Osmolyte Production and Abiotic Stress Mitigation

Beyond the mentioned ACC deaminase, endophytes directly help plants cope with drought, salinity, and heavy metal stress. Endophytes can produce osmolytes like proline, glycine betaine, and trehalose. These compounds help maintain cell turgor pressure and protect cellular structures (like enzymes and membranes) under water-deficit or high-salinity conditions. They can also enhance antioxidant production (e.g., catalase, superoxide dismutase) to detoxify reactive oxygen species (ROS) that accumulate under stress. Leads to significantly improved plant growth and survival under challenging environmental conditions, which is critical in the face of climate change (22).

Modulation of Carbon Metabolism and Photosynthesis

Endophytes can influence the plant's primary carbon metabolism, enhancing its energy production capacity. They can increase the activity of key photosynthetic enzymes (like RUBISCO) and chlorophyll content, leading to a higher photosynthetic rate. Some endophytes also influence sugar metabolism and partitioning, ensuring better carbon allocation to growing parts of the plant. Results in increased biomass accumulation, higher yields, and more energy for the plant to invest in other defense and growth processes (23).

The ISR and SAR distinction

Bacterial and fungal endophytes significantly boost a plant's defensive capacity by priming an innate immune response known as Induced Systemic Resistance (ISR). This primed state is orchestrated mainly through jasmonic acid and ethylene hormones, preparing the plant to mount a swift and robust defense against herbivorous insects and necrotrophic fungi (24). This mechanism differs from Systemic Acquired Resistance (SAR), which is typically initiated by pathogen attack and is dependent on salicylic acid signaling and the widespread activation of pathogenesis-related (PR) genes to combat biotrophic pathogens (25). A key distinction lies in the strategy of these endophytes: bacterial strains often elicit a classic ISR response, whereas certain fungal endophytes can uniquely stimulate elements of the SAR pathway or fine-tune the interplay between SA and JA signaling. This sophisticated regulation, a form of defense priming, equips the plant with versatile protection against a wider array of threats (26). Consequently, by activating ISR and sometimes co-opting SAR components, endophytic microbes work in concert to fortify the plant's immune system, offering a sophisticated, multi-layered approach to sustainable plant protection.

Ecological Significance and Agricultural Potential

Their associations, ranging from mutualism to more specialized symbioses, have been observed in both domesticated and wild plant species (27). By replacing or supplementing synthetic fertilizers, such microbial processes offer an eco-friendly strategy for sustainable agriculture. Considering the extensive reliance on chemical phosphate fertilizers, microbial solubilization of fixed phosphorus is emerging as a sustainable alternative (28). Despite their ecological and agricultural significance, only a small fraction of the vast endophytic diversity estimated to include millions of microbial species has been explored in depth (29). The growth-promoting factors, nutrient provision and hormonal balance create a vigorous, stress-resilient host. This strong host, in turn, provides a premier home for the defensive endophytes. The endophytes, living within this thriving partner, return the favor by serving as in-built, always-active defense system. This unexplored reservoir represents a frontier in microbial ecology, where understanding the complex signaling and colonization dynamics between the endophyte and the host plant is key to developing effective microbial consortia or bio-inoculants. Unlocking this hidden biodiversity and deciphering these interactions hold the promise of revolutionizing sustainable crop management, enhancing food security, and significantly reducing our reliance on chemical inputs.

Diversity and Ecological Niches of Endophytes

Endophytes are widely distributed across plant ecosystems, where their ability to colonize internal tissues leads to a spectrum of interactions ranging from symbiotic and mutualistic to commensal and trophobiotic associations. These intimate partnerships allow endophytes to persist in diverse hosts without causing disease symptoms, making them integral but often overlooked members of plant microbiomes. Both bacterial and fungal endophytes have been extensively studied, with commonly reported taxa including *Colletotrichum*, *Enterobacter*, *Phomopsis*, *Cladosporium*, and *Phyllosticta* (30) (31). Similarly, bacterial genera such as *Pseudomonas*, *Burkholderia*, and *Bacillus*, along with fungi like *Beauveria bassiana*, *Aspergillus nidulans*, and *Metarhizium robertsii*, are particularly well known for their metabolic versatility. These organisms produce a broad spectrum of bioactive compounds, including antibiotics, antifungal and antiviral agents, volatile organic compounds, immunosuppressants, and even anticancer metabolites, which directly contribute to enhanced plant growth, protection, and yield. Among them, *Metarhizium robertsii* has drawn special attention as an effective biocontrol agent due to its capacity to combine endophytic colonization with the production of potent secondary metabolites. One of the key attributes that make endophytes highly suitable for biocontrol is their occupation of ecological niches similar to those of phytopathogens. By colonizing the same internal environments, they are positioned to outcompete or inhibit pathogenic invaders (32)(33). Several bacterial genera, including *Agrobacterium*, *Achromobacter*, *Bacillus*, *Acinetobacter*, *Brevibacterium*, *Pseudomonas*, and *Xanthomonas* have been consistently reported as prominent endophytes in different plant hosts (34). Among these, *Bacillus* species stand out for their commercial relevance, accounting for nearly half of the currently marketed biological control formulations. Their stability, wide adaptability, and proven antagonistic effects have made them dominant players in microbial biocontrol strategies. The ecological significance of fungal endophytes has also been demonstrated in early studies. For instance, *Phomopsis oblonga* was first reported to defend elm trees against the larvae of *Physocnemum brevilineum* (Coleoptera: Cerambycidae) by producing insecticidal metabolites (35). This discovery underscored the potential of endophytes to protect plants not only from pathogens but also from herbivorous insects, further broadening their role as multifunctional allies in plant ecosystems.

Endophytes as Sustainable Alternatives to Chemical Pesticides

The extensive use of chemical pesticides has raised serious concerns for human health, ecological safety, and global biodiversity. Classified as acutely toxic agents, pesticides have been linked to respiratory illnesses, neurodegenerative disorders, immune suppression, hormonal disruption, reproductive defects, and certain cancers, particularly among farming communities with chronic exposure (36)(37). Food chain contamination adds to the risks, with residues often exceeding permissible limits, as observed in India, where regulatory bans on several pesticides have already been enforced (38). These alarming realities have intensified the search for safe and sustainable alternatives to chemical-based pest control. Endophytic microorganisms offer a promising solution by naturally reducing pest and pathogen pressure within plants. They achieve this through the production of diverse bioactive metabolites, including alkaloids, lectins, and proteins that disrupt herbivore physiology and behavior. For example, alkaloids synthesized by grass-associated endophytes alter insect life cycles and feeding capacity, thereby protecting host plants from herbivory. Similarly, lectins, a class of carbohydrate-binding proteins, have been shown to provide insect resistance in several crops. In *Pinellia ternata*, an herb species native to East Asia, endophytic lectin production significantly reduced damage from rice pests such as *Sogatella furcifera* (Hemiptera: Delphacidae), which cause characteristic “burning by suction” symptoms (39). Beyond their natural metabolites, endophytes also hold potential as genetically engineered pest-management tools. Recombinant DNA technology has enabled the insertion of insecticidal genes into endophytes to broaden their protective capacity. Early pioneering work demonstrated the successful introduction of *Bacillus thuringiensis* toxin genes into *Clavibacter xyli* subsp. *cynodontis*, which conferred resistance to insect feeding when reintroduced into host plants (40). Similarly, lectin-coding genes from *P. ternata* were engineered into *Enterobacter cloacae*, producing recombinant endophytes that effectively suppressed rice leafhopper infestations (41)(42). These advances highlight the versatility of endophytes as both natural and engineered biocontrol agents. On a global scale, the integration of endophytes and other microbial biocontrol agents is rapidly gaining traction. In Brazil, millions of hectares have been treated with bioagents such as *Trichoderma harzianum*, *Beauveria bassiana*, and *Metarhizium anisopliae* (Metchnikoff) Sorokin, demonstrating substantial effectiveness against key pests (Parra, 2019). Notably, *M. anisopliae* was the first endophyte reported for the biological control of the sugarcane leafhopper (*Hemiptera: Cercopidae*), successfully colonizing plant tissues and reducing pest infestations. Similar trends are emerging in China, where the biocontrol market surpassed USD 100 million in 2020, with projections indicating rapid growth to USD 3 to 5 billion globally (43). In addition to pest suppression, endophytes also contribute to environmental sustainability by participating in bioremediation. Several species are capable of degrading or detoxifying residual pesticides, fungicides, and other agrochemicals, transforming them into less harmful compounds and thereby reducing their persistence in ecosystems. This dual role of biocontrol and bioremediation positions endophytes as pivotal tools in the transition away from chemical-intensive agriculture toward ecologically harmonious systems.

Insect pest management by bacterial endophytes

Bacterial endophytes are beneficial microorganisms that live in close association with plant tissues, including leaves, stems, and branches, without causing harm to their hosts (44). These microbes enhance plant vigor and confer resistance against a wide range of insect pests while supporting growth under stressful environmental conditions. Many strains of bacterial endophytes, exhibiting diverse morphologies (45), are commercially available and play significant roles in pest suppression and the induction of systemic resistance (46). Contact with these bacteria can trigger Induced Systemic Resistance (ISR), leading to the production of defense-related compounds and the development of Systemic Acquired Resistance (SAR) (47). Bacterial endophytes have demonstrated remarkable efficacy against a variety of insect pests across different crops. For instance, inoculation with *Bacillus amyloliquefaciens* induces lipopeptide production in plants, enhancing resistance to the fall armyworm (*Spodoptera frugiperda*) and reducing pest body weight (48). Similarly, the Gram-negative rod-shaped bacterium *Enterobacter cloacae* has been successfully applied against the White-Backed Plant Hopper (*Sogatella furcifera*) in paddy through the production of Pinellia ternata agglutinin (PTA) protein (49). In Brassicaceae crops, pests such as the Diamondback Moth (*Plutella xylostella*) cause severe yield losses globally, but endophytic bacteria including *Enterobacter cloacae*, *Alcaligenes piechaudii*, and *Klebsiella ascorbata* have proven effective in their management (50). (Fig 2)

Table 1: Entomopathogenic activity of endophytic bacteria against target insect species in different plants.

Endophytic bacteria	Plant Species	Target pest	Action	Reference
Bacillus thuringiensis	*Brassica oleracea var. Capitata*	*Plutella xylostella (Lepidoptera: Plutellidae)*	Increased larval mortality percentage	(51)
Burkholderia pyrrocinia	*Populus* sp.	*Bombyx mori Lepidoptera: Bombycidae)*	Enhanced toxicity	(52)
Enterobacterium cloacae	*Oryza sativa*	Sogatella furcifera (Hemiptera: Delphacidae)	Enhances Larval mortality	(53)
Pseudomonas azotoformans	*Brassica olerace*	*Mamestra brassicae*	Decrease the survival of caterpillars	(54)
Pseudomonas spp.	*Calotropis procera*	*Galleria mellonella*	Increased larval mortality	(55)
B. substilis	Allanmands cathartica	*Spodoptera litura*	Larval mortality	(56)
B.licheniformis, B. pumilus	Combretum molle	*Ceratistis capitata*	Decrease survival	(57)
Streptomyces sp. TP-A0595 Aeromicrobium ponti	Mangifera indica Linn Bauhinia guianensis	*Sternochetus mangiferae*	Decrease larval survival	(58)

Other studies have highlighted the insecticidal activity of *Pseudomonas fluorescens* strains CHAO and Pf-5, which caused high mortality in the tobacco hornworm (*Manduca sexta*) and the greater wax moth (*Galleria mellonella*), even at suboptimal doses (59). In addition, treatment of cotton with plant growth-promoting rhizobacteria such as *Bacillus* spp. significantly reduced aphid populations (60). Similarly, *Bacillus subtilis* effectively suppressed *Bemisia tabaci* on tomato and aphids on cowpea, demonstrating its superior efficacy among multiple PGPR strains (61). In maize, *Serratia* sp. exhibited entomopathogenic activity against *Diabrotica virgifera virgifera* rootworms, with bacterial populations increasing in response to infestation, and was also effective against the pod bug *Riptortus pedestris* in cowpea (62). Beyond pest management, bacterial endophytes contribute to the biodegradation of xenobiotics, highlighting their ecological versatility. For example, *Acinetobacter* and *Pseudomonas* sp. isolated from contaminated soils were able to degrade organophosphates such as chlorpyrifos and diazinon by 80–88% (63). Endosymbiotic bacteria from the gut of the citrus mealybug (*Planococcus citri*), including *Bacillus* and *Pseudomonas*, have been shown to degrade both chlorpyrifos and polyethylene, using carbon from polyethylene as an energy source via enzymatic solubilization. These findings illustrate that bacterial endophytes not only support plant health and pest suppression but also offer potential for environmental remediation.

Action mechanism of bacterial endophytes

The studies done at the biochemical level unraveled the mechanism behind the degradation of the pesticides and induction of pesticidal resistance. Various enzymes, such as lipases, which are degrading enzymes that endophytic microorganisms produce which catabolise the long chain of hydrocarbons. The degradation of important enzymes such as lipase in the thermophilic bacterium *Bacillus* sp (64) is due to the degradation of hydrocarbons present. The consortium of benevolent bacteria present in the plants triggers the induced systemic resistance through signal transduction pathway. As a result, a torrent of different pathogenesis-affiliated proteins (PR proteins) and defense enzymes, including lipoxygenase, chitinases, peroxidases (PO), and polyphenol oxidases (PPO), are released. The plant will be protected against disease growth and herbivore insect feeding by the enzymes and proteins secreted as part of its defensive mechanism. (65) reported that the increase of plant defense and induced systemic resistance (ISR) mediated by beneficial bacteria is also an outcome of systemic acquired resistance (SAR). The defense mechanism is mainly contributed to the release of jasmonic acid (JA), and its related members, have been actively playing a role in the defense mechanism when insects attack the plant. It causes the induction of some proteins such as lipoxygenase, arginases, ascorbate oxidases, and proteinase. The chitinase production is also stimulated, which directly acts on the exoskeleton of insects.

Role of fungi as endophytes in insect pest management

In the five kingdom system of classification, the fungi are eukaryotic, unicellular or multicellular heterotrophic organisms that exhibit a broad range in their survivability. A diverse work has been done on fungi as endophytes, but the most quintessential work as an endophyte has been carried out on the endophytic fungus *Phomopsis oblonga*, which gives protection to trees against the beetle *Physocnemum brevilineum* (66). The era in which insect pests are managed by employing living entities, fungal endophytes are taking a leading role in controlling disease across diverse crops. This approach profoundly involves species such as *Beauveria*, *Clonostachys*, and *Isaria*, which are isolated from their respective host plants (67). Additionally, Beauveria bassiana has been found in investigations on the European corn borer (*Ostrinia nubilalis*), the pink borer (*Sesamia calamistis*) in maize, and poppies stem gall produced by cynipid gall wasp (68). Fungal endophytic entomopathogens boost plant defense by producing secondary metabolites that act as a curative measure against various insects. Among these, alkaloids such as lolines, aminopyrrolizidine, peramine, and pyrrolopyrazine exhibit broad-spectrum insecticidal activity. For example, they are effective against the Argentine stem weevil and have been successfully employed to control major pests in cereals, including the aphids *Rhopalosiphum padi* and *Schizaphis graminum* (69).

Table 2: Target pest of diverse endophytic fungi by the entomopathogenic activity in different plants.

Endophytic Fungus	Plant Species	Target pest	Action	Reference
Aspergillus nidulans	*Lantana camara*	*Spodoptera littoralis* (Lepidoptera: Noctuidae)	Larval mortality	(70)
Beauveria bassiana	*Gossypium hirsutum*	*Aphis gossypii* (Hemiptera: Aphididae)	Decreased reproduction	(71)
	Solanum lycopersicum	*Spodoptera exígua* (Lepidóptera: Noctuidae	Decrease in the development of larvae	(72)
	Triticum aestivum	*Spodoptera littoralis* (Lepidoptera: Noctuidae)	Increased mortality of Larvae	(73)
	Zea mays	*Spodoptera frugiperda* (Lepidoptera: Noctuidae)	Increased mortality of Larvae	(74)
	Vitis venifera	*Aphis illinoisensis* (Hemiptera: Aphididae)	Enhanced virulence	(75)
Metarhizium Robertsii	*Zea mays*	*Agrotis ipsilon* (Lepidoptera, Noctuidae)	Lessens growth	(76)
Metarhizium anisopliae	*Brassica napus*	*Plutella xylostella* (Lepidoptera:Yponomeutidae)	Increased mortality	(77)
Phomopsis oblonga	*Ulmus minor*	*Physocnemum brevilineum* (Coleoptera: Cerambycidae)	Reducing the spread of the disease	(78)
Purpureocillium lilacinum	*Gossypium hirsutum*	*Aphis gossypii* (Hemiptera: Aphididae)	Low reproducing rate	(79)
Trichoderma strigosellum	*Eucalyptus urophylla*	*Atta* spp. *Acromyrmex* spp. Hymenoptera: Formicidae)	Infect the ant's nest	(80)
Rhizophagus sp.	*Solanum lycopersicum*	*Spodoptera exígua* (Lepidóptera: Noctuidae)	Decrease development of larvae	(81)

Beyond conferring resistance against insect pests, fungal endophytes also help plants tolerate abiotic stresses and improve nutrient availability. With the indispensable use of pesticides posing high risks to humans and other organisms, fungal endophytes represent a promising and sustainable long-term substitute for insect pest management (82).

Mechanism of action of Fungus

The colonization of insects by entomopathogenic fungi begins with the penetration of fungal hyphae, which initially form thickened and highly branched structures on the insect cuticle. These hyphae progressively penetrate the integument and reach the hemolymph, where they differentiate into yeast-like asexual spores called blastospores. Blastospores function as nutrient-absorbing structures and actively secrete insecticidal metabolites such as beauvericin and destruxins, which disrupt physiological processes in the insect and result in rapid mortality (83). The initial infection relies on the adhesion of fungal conidia to the insect cuticle, a process optimized at temperatures between 23–30°C, followed by germination and development of specialized structures. In *Metarhizium robertsii*, the adhesin protein MAD1 mediates the attachment of conidial spores to the cuticle, whereas in *Beauveria* species, hydrophobins play a similar role in promoting adherence (84). During germination, mechanical pressure exerted by the growing hyphae results in the formation of appressoria, which facilitate cuticle penetration. The secretion of degradative enzymes like proteases, lipases, and amylases allows the fungus to break down the insect's protective layers, a critical step for successful colonization and subsequent systemic infection. Beyond their role as insect pathogens, entomopathogenic fungi such as *M. robertsii* have been shown to colonize plants endophytically, particularly within roots, where they enhance plant growth and provide protection against root-feeding insect larvae. Following fungal infection, insect larvae are killed by fungal metabolites, and their decaying biomass serves as a source of nitrogen and carbon, benefiting both the plant and the fungus (85). Similarly, grass species such as *Achnatherum robustum* host endophytes of the genus *Epichloe*, which produce alkaloid compounds that are toxic to sap-sucking pests like aphids, thereby offering a natural and sustainable form of plant protection (86). This dual role of entomopathogenic fungi as both insect pathogens and plant endophytes, highlights their potential for integrated pest management, where they can simultaneously enhance plant health and suppress pest populations, providing a sustainable alternative to chemical pesticides (Fig.3).

Endophyte Mediated Modulation of Natural Enemy Populations

Endophytic microorganisms, residing in soil and plant tissues such as leaves, flowers, seeds, and roots, influence arthropod communities and play a critical ecological role by indirectly affecting natural enemies of herbivores (87). Both fungal and bacterial endophytes have been shown to enhance Integrated Pest Management (IPM) strategies by modulating predator and parasitoid efficiency (88). The colonization of plants by endophytes alters plant defensive compounds, alkaloids, and nutrient profiles, which affects herbivore feeding and, consequently, the abundance, growth, and foraging behavior of natural enemies (89). Research indicates that applying low doses of entomopathogenic fungi can effectively suppress pests while preserving beneficial insect populations. This approach minimizes harm to key predators like ladybird beetles (*Coccinella* spp.) and lacewings (*Chrysoperla carnea*) and maintains parasitoid activity, though the timing between fungal application and natural enemy release is critical for optimal prey consumption and parasitoid oviposition (90). Fungal endophytes can reduce the nutritional quality of prey, leading to higher consumption rates by predators, though in some cases natural enemies avoid prey from fungus-colonized plants (91). Colonization by endophytes also influences plant signaling and volatile emission, which can enhance herbivore feeding but may negatively impact predators due to the transfer of plant-derived alkaloids and mycotoxins through the food chain, resulting in reduced survival, longevity, and reproduction (92). Overall, endophytes modulate interactions across multiple trophic levels, affecting herbivores and their natural enemies, with consequences for pest dynamics and biological control.

Future Scope

Endophytes, as beneficial microbes, have coexisted within plant tissues for millennia, forming symbiotic relationships that enhance plant health, confer resistance to abiotic stresses, insect pests, and inhibit the establishment of pathogens. The utilization of endophyte-plant interactions presents a sustainable strategy for diminishing chemical reliance in both food and non-food crop production. Realizing the biotechnological promise of these partnerships depends on a deeper understanding of their underlying communication mechanisms. Promising applications include sustainable biomass and bio-energy production, phytoremediation of contaminated soils, and the discovery of bioactive compounds such as anticancer agents like taxol. Beyond their established role in pest management, microbial endophytes are now being studied for their ability to promote plant development and act synergistically with low-toxicity pesticides and other biocontrol agents. Endophytes enhance integrated pest management (IPM) by improving the efficacy of natural enemies while reducing environmental impact. The identification of novel endophytic strains can promote resource sustainability and minimize reliance on harmful chemicals. Harnessing advanced biotechnologies, the precise introduction of endophytes and the engineering of their metabolic pathways present a transformative, eco-conscious paradigm for crop protection. By leveraging these microbial allies, agriculture can cultivate high-yielding, resilient production systems that are intrinsically aligned with the preservation of ecosystem integrity, positioning endophytes as a cornerstone of sustainable agronomic innovation.

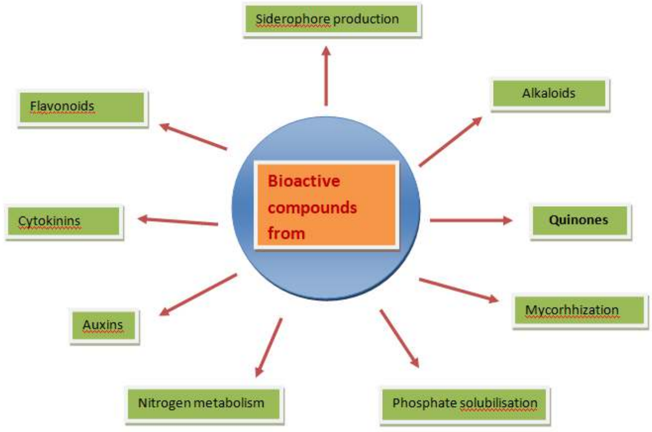

Fig 1. Potential application of the endophytes unveiled in the plant growth metabolism

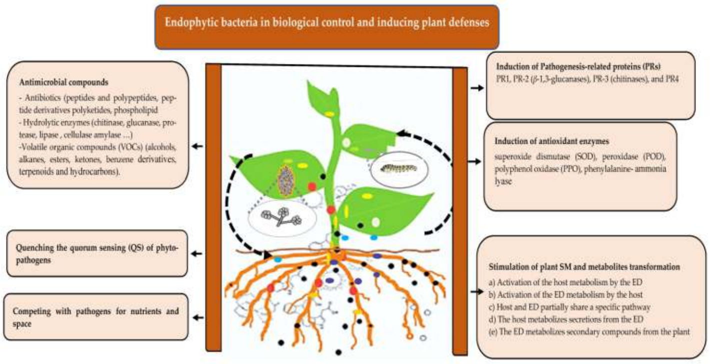

Fig 2. Mechanism of endophytic bacteria in plants in evading stress and pest management through production of different enzymes and proteins (Oukala et al.,2021)

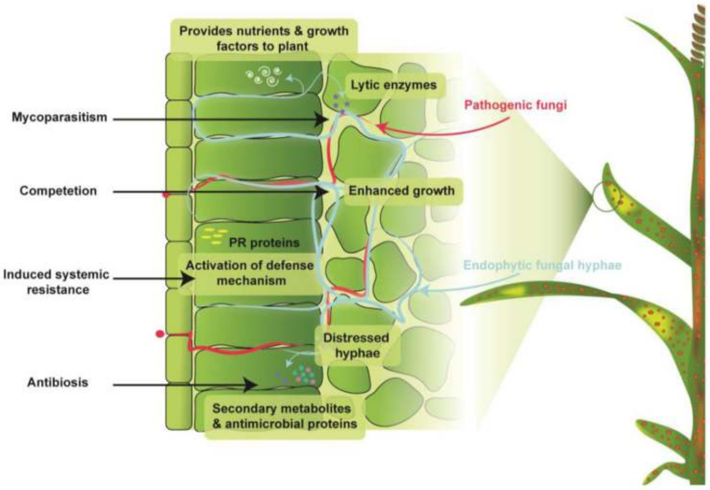

Fig.3 Mechanism of fungal endophytes in pest management through activation of various mechanisms in plants various (Akram et al.,2022)

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