Biosynthetic Potentials of Endophytic microorganism in Plant-Microbe Interactions

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Abstract

Bacteria and fungi are the main types of endophytic microorganism that colonize in internal parts of plants without causing any harm. Plant and microorganism having mutualistic relationship leads to plant growth promotion and resistance towards various phtopathogens. The various benefits of endophytic bacteria towards the plant such as plant growth promotion and biocontrol. Therefore, endophytes can be explored for their significant potential to serve as substitute to agrochemicals in various agricultural benefits. In recent years of endophytology, the concepts of holobiome association of plant and endophytes) and hologenome (combined genetic information of plant and endophytes) have attracted the least attention. The current review article is discussed about various biosynthetic features of endophytes.

Keywords

Endophytic microorganism, Plant- microbe relationship, Plant growth promotion, Biocontrol

Introduction

Endophytes, originating from the Greek words "endon" (within) and "phyton" (plant), refer to "any organism located within plant tissues."(Brader et al., 2017) In its widest and most recognized sense, endophytes are regarded as microbes that live in the internal tissues of living plants without causing immediate or obvious harm. Specifically, endophytes refer to microorganisms (including fungi, bacteria, actinomycetes, etc.) that spend part of their life cycle developing an asymptomatic relationship with a plant. (Brader et al., 2017; Ryan et al., 2007). Organisms that rely on living cells for their growth and life cycle completion are classified as "obligate," while those that predominantly thrive on the outer surfaces of plant tissues are termed "epiphytes," and those that occasionally invade the plant's endosphere are known as "opportunistic."(Vasileva et al., 2019) In this mutual relationship, both the plant and the endophytic microorganisms benefit from each other significantly.(Firáková et al., 2007) These endophytes are commonly located within the rhizosphere, and suitable entry points into the host plant include the apical root zone with its thin-walled surface root layers, in addition to the basal root zones characterized by small cracks.(Firáková et al., 2007) They can be found throughout the entire host plant, existing within cells, vascular systems, or intercellular spaces. Endophytic microbes may also enter through stomata and can be passed from parent plants to their offspring via seeds, while roots experience the greatest level of colonization through the epidermis during the emergence of lateral roots. (Montesinos, 2003)The concept of "balanced antagonism" related to asymptomatic colonization signifies that endophytic microbes can coexist within the host plant without triggering any defensive responses, enhancing the plant's self-sufficiency by producing substances akin to those of the plant. (Elsheikh et al., 2021)Investigating plant–microbe interactions helps us understand natural phenomena that influence our daily lives and could pave the way for sustainable resource management, lower environmental impacts, and reduction of pollution.(Ongaga et al., 2025) The potential benefits of utilizing these interactions for biotechnological applications are noteworthy. Utilizing existing plant–microbe connections to improve plant growth and biocontrol reduces reliance on synthetic pesticides and fertilizers, which not only lowers costs but also diminishes the effects of chemical inputs on beneficial flora and fauna. (Li et al., 2021)

As their name indicates, endophytic microorganisms reside within a plant in the intercellular spaces of various plant structures, such as stems, roots, petioles, and leaves, without causing any noticeable symptoms of disease or poor health. The symbiotic relationship between the host plant and its endophytes has been thoroughly researched, demonstrating how the plant offers protection and nourishment to the endophytes, which in return produce specific substances with bioactive properties (including antiviral, plant growth-promoting, antibacterial, antifungal, and insecticidal activities) to boost the growth and competitiveness of the plant in natural environments. These endophytic organisms aid in protecting their host plants from pathogens by releasing bioactive secondary metabolites under challenging environmental conditions. Endophytic organisms are increasingly recognized as a vital part of biodiversity, with their distribution varying based on the type of host. Almost all vascular plants are known to harbor endophytic entities, particularly those valued for their medicinal qualities, which are thought to aid in the development of therapeutic compounds. Although endophytic microbes remain largely unexplored, numerous studies suggest that they are a significant source of therapeutic agents. It is estimated that around 300,000 plant species in underexplored areas host at least one type of endophytic microbe.As their name indicates, endophytic microorganisms reside within a plant in the intercellular spaces of various plant structures, such as stems, roots, petioles, and leaves, without causing any noticeable symptoms of disease or poor health (Strobel and Daisy, 2003). The symbiotic relationship between the host plant and its endophytes has been thoroughly researched, demonstrating how the plant offers protection and nourishment to the endophytes, which in return produce specific substances with bioactive properties (including antiviral, plant growth-promoting, antibacterial, antifungal, and insecticidal activities) to boost the growth and competitiveness of the plant in natural environments (Strobel and Daisy, 2003). These endophytic organisms aid in protecting their host plants from pathogens by releasing bioactive secondary metabolites under challenging environmental conditions (Strobel and Daisy, 2003). Endophytic organisms are increasingly recognized as a vital part of biodiversity, with their distribution varying based on the type of host. Almost all vascular plants are known to harbor endophytic entities, particularly those valued for their medicinal qualities, which are thought to aid in the development of therapeutic compounds (Strobel and Daisy, 2003). Although endophytic microbes remain largely unexplored, numerous studies suggest that they are a significant source of therapeutic agents. It is estimated that around 300,000 plant species in underexplored areas host at least one type of endophytic microbe (Strobel and Daisy, 2003). (Das et al., 2025)Consequently, the presence of functionally diverse endophytes plays an essential role in ecosystems abundant in biodiversity. Endophytic microbes can linger within host cells for prolonged periods. (Vasileva et al., 2019)The misuse of chemical fertilizers to improve crop yields is significantly harming soil and environmental health. However, the agricultural sector is projected to see an increasing demand for fertilizers to satisfy the needs of a steadily growing population. (Agrawal & Bhatt, 2023)Given the current issues surrounding global climate change, achieving sustainable agricultural production is a notable challenge. Implementing certain strategies, such as using beneficial microbes linked to plants in agriculture, can enhance plant growth through several mechanisms and aid in alleviating various biotic and abiotic stresses, potentially acting as effective solutions in these contexts.(S. Singh et al., 2021).

Bacterial Endophytes

For plants to successfully thrive in their ecological environment, they develop mutualistic relationships that benefit various living organisms within the ecosystem. (Watts et al., 2023). One such beneficial interaction is the partnership between microorganisms and plants. Certain bacteria that colonize plant tissues establish a close relationship with their host plant and actually provide advantages under both optimal and adverse conditions.(Mei & Flinn, 2010) These endophytic bacteria offer their host plants benefits, including assistance in overcoming growth-limiting biotic and abiotic factors. Endophytic bacteria enhance the stress tolerance of their host plant, induce allelopathic effects, and promote its growth. (Kushwaha et al., 2020). Bacterial endophytes have been extracted and classified from a variety of plant hosts, environments, and different plant parts, such as root tissues, stems, leaves, seeds, fruits, tubers, ovules, and nodules.(Mei & Flinn, 2010) . However, bacterial endophytes are found more frequently in root tissues than in aerial parts of the plant. Several studies have documented the growth-enhancing capabilities of bacterial endophytes on various crops, such as rice, wheat, potato, canola, tomato, and others. A number of research investigations have indicated the significant agro-biotechnological potential of utilizing endophytic bacteria as bio-inoculants to promote a sustainable, eco-friendly, and long-lasting agricultural production system.(Gamalero et al., 2020).

Fungal Endophytes

Fungal endophytes form a close, mutually advantageous relationship with their plant hosts, as they help their hosts endure various biotic and abiotic stresses.(Gamalero et al., 2020) In return, these endophytes receive nutrients and protection from the plants. Fungal endophytes inhabit various plant tissues, including stems, fruits, flowers, roots, leaves, and branches, doing so without causing any noticeable symptoms.(Kushwaha et al., 2020) They represent a vital part of the extensive biodiversity within the fungal kingdom. It is well recognized that fungal endophytes provide their plant hosts with beneficial outcomes, including reducing or preventing damage from pests or harmful insects.(Morsy et al., 2020).

Additionally, studies show that plants associated with these fungal endophytes exhibit a reduced vulnerability to the harmful impact of pests. These endophytes provide such advantages to their host plants by disrupting the growth and developmental stages of the pests; they also influence the feeding behaviors and reproductive cycles of these pests, ultimately affecting their chances of survival. (Morsy et al., 2020)The reduction of pest damage linked to fungal endophytes has been particularly noted in maize plants. Similar findings have been reported for pest management in tomato, cotton, and coffee plants, as well as in banana, faba bean, and common bean plants. Other researchers have also documented the positive effects of fungal endophytes in reducing and controlling pest damage in plants. (Kar et al., 2023)The reduction of damage through pest control by fungal endophytes can be linked to their production of secondary mycotoxigenic metabolites in their host plants, which are harmful to the pests. Another significant mutual benefit of the relationship between endophytic fungi and plant hosts is the ability of the endophyte to provide traits that enhance tolerance to both abiotic and biotic stresses in its host, thus aiding the plant in improving its growth and becoming less vulnerable to diseases. Fungal endophytes have been shown to be significant sources of biologically active compounds. (Kar et al., 2023)They can synthesize essential plant hormones like piperine, gibberellic acid, and indole-3-acetic acid, which are necessary for promoting plant growth. Additionally, they have the ability to inhibit pathogens that cause disease in plants and help plants withstand salinity and other stressors. Recent research indicates that endophytic fungi are crucial functional players within the ecosystem.(Tufail et al., 2022) The main benefits they provide in relation to plants include their capacity to make essential growth-enhancing nutrients accessible to the plant; they assist in controlling harmful plant pests, pathogens, nematodes, and other damaging insects; they aid in alleviating environmental stress; and they are also valuable for the bioremediation of environmental pollutants. They are able to accomplish these benefits through various mechanisms. Additionally, they have been recognized as a potential source of bioactive inoculants that may help achieve agricultural sustainability. (Wu et al., 2021)Given the significant agro-biotechnological advantages presented by endophytic bacteria and fungi, it is understandable that there has been a surge of interest in finding safe, eco-friendly, and sustainable methods to enhance agricultural production. (Eid et al., 2021)The use of endophytic microbial formulations has emerged as an appealing alternative for sustainable crop intensification, particularly due to fungal endophytes' ability to generate essential compounds that foster plant growth, deter harmful pests and pathogens, and provide plants with traits that enhance immunity and resilience to abiotic stresses. (L. P. Singh et al., 2011).

Colonization of the endophytic microorganisms in plants

A variety of microorganisms, including both bacteria and fungi, are recognized as endophytes that reside within plant tissues.(Eid et al., 2019) Endophytes dwell within the internal tissues of plants, comprising a range of bacterial and fungal species that collectively form the "plant endomicrobiome," which can induce various physiological responses in the plant. Figure 1 illustrates the colonization and benefits associated with endophytic microorganisms within plants.(Godara & Ramakrishna, 2022) These microorganisms can enter plants as endophytes through either vertical or horizontal transmission methods. In vertical transmission, endophytes are transferred to seeds via vascular connections. Following germination, it is believed that these endophytic populations proliferate and disseminate to different parts of the plant, including roots and shoots. On the other hand, horizontal transmission primarily involves the sourcing of endophytes from the soil, requiring interaction at the rhizoplane before migrating into the intercellular spaces of the root. The diversity and abundance of associated endophytic microbial communities are mainly determined by the host plant and the specific tissues involved. (Frank et al., 2017)Consequently, seeds play a vital role in the microbiome, as they can contain microbial partners that significantly enhance plant competitiveness and growth. Certain microflora may be transferred through vertical transmission. Furthermore, endophytic microorganisms residing in the seeds are thought to be more effective at helping the plant adapt to challenging environmental conditions than those located in other plant tissues. They may also display cell motility and phytase activity, which allows them to move freely within the plant and accumulate in the seeds before they harden.(Wang & Zhang, 2023)

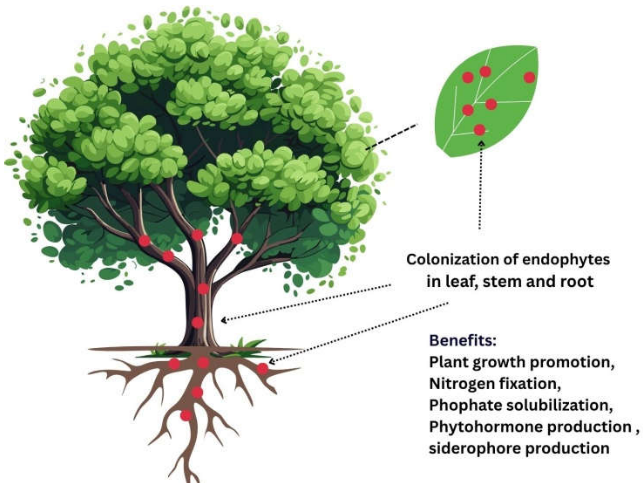

Figure 1. Colonization of endophytic microorganisms within plants and their benefits.

Autofluorescent proteins (AFP) can be a valuable method and tool for visualizing biofilms, aiding in the study of plant-microbe interactions. These visualization methods also include gene expression research utilizing GFP (green fluorescent proteins), which involves integrating the GFP gene into the bacterial chromosome and employing a plasmid containing GFP for the visualization of cloned cells through techniques such as confocal, epifluorescence, or laser scanning microscopy.(Kumar & Nautiyal, 2022)

The host plant establishes a symbiotic relationship with a wide variety of soil microorganisms. In the beginning, endophytic fungi may adhere to the root surfaces and form structures known as appressoria. Following this, these attachments penetrate the outer layer of the roots and invade the internal plant tissues. Endophytic fungi primarily exhibit two diffusion patterns; the first mechanism involves the vertical transmission of fungi into the seeds of progeny from the parent plants, resulting in offspring infection. Infected seeds germinate under favorable environmental conditions, allowing the fungi within the seeds to infiltrate the seedlings after germination. (Pathak et al., 2022)Typically, endophytic fungi emerge from the nutrient-rich rhizosphere, which is also home to insects and animals that feed, along with airborne fungal spores. Many endophytic fungal microbes disperse via spores or hyphal fragments present in the aboveground parts of plants, aided by biotic factors such as insects or herbivores, or abiotic agents like rain and wind, linking various plant hosts through a network of fungal endophytes. In cucumber roots colonized by endophytes, several phenomena were observed, including heightened chitinase activity, necrosis of the penetration peg, and the formation of fluorescent products in the intercellular spaces. This may be due to the significant production of extracellular enzymes by endophytic fungi.(Mei & Flinn, 2010).

Benefits of endophytic microoranisms in plants

Endophytes have the ability to enhance plant growth both directly and indirectly, as illustrated in figure 2. When rhizospheric bacteria transition into endophytes, it is believed that these endophytes can retain their traits within the host plant.(Gaiero et al., 2013)

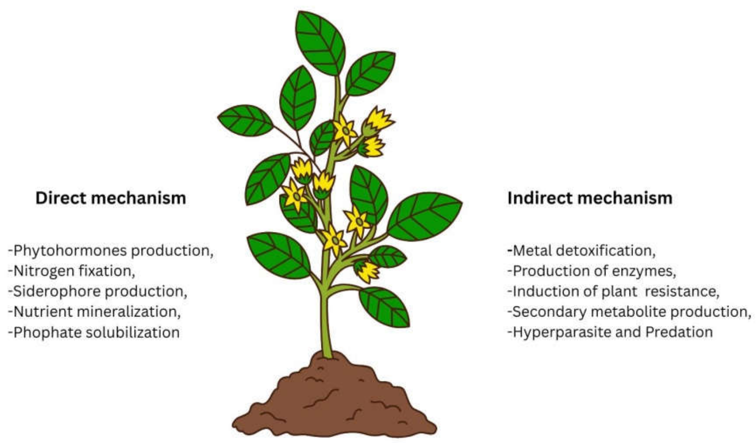

Figure 2. Mechanism of endophytic microoranisms for plant growth

Direct mechanisms

Endophytic microorganisms assist host plants in multiple ways to boost their growth by aiding in the absorption of essential nutrients, which ultimately results in higher crop yields. A typical example is the nitrogen fixation carried out by specific endophytes found in leguminous plants. Additionally, many studies have shown that endophytic bacteria can effectively engage with non-leguminous crops, creating a collaborative relationship for nitrogen fixation. (Jha et al., 2018)The promotion of plant growth can be achieved through various mechanisms, such as the generation of plant hormones like gibberellins, indole-3-acetic acid (IAA), and the modulation of ethylene and cytokinins. Numerous endophytes have exhibited the capability to produce the enzyme ACC (1-aminocyclopropane-1-carboxylate) deaminase, which can affect plant physiology by reducing ethylene levels, as ethylene acts as a hormone that restricts plant growth. The strain of Penicillium citrinum generated significantly higher levels of biologically active gibberellins compared to the wild type of Gibberella fujikuroi, indicating its potential as a source of gibberellic acid (GA3). Research has indicated that various fungal endophytes contribute to increased plant height, biomass, and tiller number across different crops. (Ghosh et al., 2020; Munir et al., 2022)The seed-borne endophytic fungus Stagonospora spp. enhanced the productivity of Phragmites australis (Cav.) Trin. ex Steud., while another endophytic fungus promoted growth in peppermint. Biological nitrogen fixation (BNF) of atmospheric N2 is crucial in improving soil fertility and supporting plant health. The process of transforming atmospheric nitrogen dioxide into ammonia and nitrate occurs with the nitrogenase enzyme complex and is known as BNF.(Saikkonen et al., 1998) Nitrogen is viewed as a critical nutrient that restricts plant growth. Diazotrophs are the bacteria that facilitate this form of nutrition conversion. While some diazotrophs are capable of fixing nitrogen in association with their hosts, others live independently in the environment. Certain symbiotic bacterial endophytes provoke physiological and structural changes in plant roots, leading to the development of specialized nodules. Soil microorganisms, such as actinomycetes present in lichens and cycads, also accomplish nitrogen fixation by forming symbiotic associations. Phosphorus (P) is essential for the growth and development of plants. Approximately 95% of phosphorus in the soil is in insoluble forms, immobilized, or has combined with other minerals (like rock phosphate and tricalcium phosphate). (Wu et al., 2021)When phosphorus is added to the soil through inorganic fertilizers, it eventually binds to soil components, making it unavailable for plant uptake. Phosphate solubilizing bacteria, predominantly endophytic bacteria located in plant tissues and the rhizosphere, assist in mineralizing and solubilizing phosphate through biological processes to enhance phosphorus availability in the soil. The most effective groups of phosphate solubilizers comprise Enterobacter, Pseudomonas, Mesorhizobium, Bacillus, Achromobacter, Rhizobium, and Acinetobacter. These endophytic microorganisms increase the availability of phosphorus by transforming insoluble forms using processes such as organic acid production, ion exchange, soil acidification, and chelation. Moreover, in conditions where phosphorus is scarce, endophytic microorganisms can absorb the dissolved phosphorus, lessen its fixation in the soil, and improve its uptake by the host plant, thus making it more accessible.(Guha & Mandal Biswas, 2024)

Indirect beneficial mechanisms

Plants adapt to various challenging environmental conditions or abiotic stresses, including low temperatures, drought, high salinity, and diseases. Endophytic microorganisms support plants in navigating these difficulties through several indirect methods, which also promote the increase of secondary metabolites (such as pharmaceuticals or essential medicinal compounds) within the plants.(Babalola & Adedayo, 2023) These endophytic microbes help host plants tackle the aforementioned stressors through various indirect approaches. They are also crucial in bioremediation using different strategies, which include alleviating heavy metal stress, removing harmful greenhouse gases, and inhibiting pest development on plants. Additionally, endophytic microbes support phytoremediation by reducing metal-related toxicity. Furthermore, for plants that contain endophytes with the necessary metabolic capabilities and degradation pathways to decrease phytotoxicity and improve degradation, the plant-endophyte relationships can be utilized to rehabilitate degraded lands and groundwater sources. Endophytic bacteria also aid in the extraction of heavy metals. Additionally, endophytes are proficient in degrading polyaromatic hydrocarbons (PAH).(Verma et al., 2022).

Agricultural Potential of Endophytic Microorganisms

The excessive use of agrochemicals to enhance crop yields has resulted in notable environmental and health problems. Consequently, there is a growing interest in safer alternative methods to minimize or eliminate chemical usage. This emphasizes the importance of employing endophytic microorganisms, which have natural abilities to promote plant growth and defend against pests through various biosynthetic pathways. Their methods for enhancing plant growth and development mainly involve the solubilization of nutrients in the soil, nitrogen fixation, the synthesis of phytohormones, and lowering ethylene levels by producing ACC deaminase (1-amino-cyclopropane-1-carboxylate).(Guha & Mandal Biswas, 2024) Indirect methods include the generation of secondary metabolites that boost plant resistance to different pathogens. These mechanisms are anticipated to function effectively among seed endophytes. As research into plant-associated bacteria has expanded for agricultural purposes, seed endophytes also offer promising applications. Numerous studies have pointed to the potential of Pseudomonas spp. in agriculture as entities that encourage plant growth and biocontrol. Additionally, various endophytic bacterial species, such as Azospirillum, Azoarcus, Enterobacter, Serratia, and Stenotrophomonas, have been reported to enhance plant growth through mechanisms like nitrogen fixation, phytohormone production, siderophore synthesis, and the creation of ACC deaminase. The growth-promoting effects of endophytic Bacillus spp. and Penicillium spp. have been linked to their synthesis of IAA and their capacity to solubilize phosphate.(Verma et al., 2022) Moreover, the biocontrol capabilities of endophytes are believed to support plant growth in an indirect manner. Antagonistic research on bacterial genera such as Aureobacterium, Bacillus, Paenibacillus, Phyllobacterium, Pseudomonas, and Burkholderia has demonstrated their ability to hinder pathogens like Fusarium oxysporum, Rhizoctonia solani, Sclerotium rolfsii, and Verticillium dahliae, among others. While numerous endophytic microorganisms have been recognized as viable candidates for biocontrol, products based on Bacillus are primarily marketed as microbial pesticides, fungicides, and fertilizers. Their biological safety has led to their widespread adoption in agricultural practices. In a previous study, Paenibacillus sp., Pantoea sp., and Bacillus sp. were isolated from wheat seeds, showing their capability to foster plant growth and offer resistance against F. graminearum. This indicates that Bacillus sp. can act as an endophyte within seeds and displays agricultural promise. The basis of biocontrol associated with endophytes largely relies on the production of antibiotics, lytic enzymes, and the activation of induced systemic resistance mechanisms in plants. Hence, seed endophytes can be regarded as a valuable source of microbial candidates with highly specialized functions that benefit plants.(Godara & Ramakrishna, 2022)

Features of endophytic microorganisms in plant growth promotion

Regardless of their source of isolation, endophytic microbes have demonstrated various mechanisms that provide advantages to plants. These microorganisms influence the growth and development of host plants by improving nutrient absorption and modulating phytohormone levels. Many plant-associated microbes, such as Pantoea agglomerans and Azoarcus species, have been recognized for their ability to fix atmospheric nitrogen and convert it into a form usable by plants. (Negi et al., 2023)The capacity of microorganisms to solubilize phosphate is a vital method for promoting plant growth since phosphate is critical for root and stem development, flowering, and the formation of seeds and fruits. Some endophytic microorganisms are capable of transforming insoluble phosphate compounds into accessible forms for plants through mechanisms like acidification, chelation, and exchange reactions. The phosphate-solubilizing ability of endophytic Pseudomonas species greatly boosts the growth of Pisum sativum. Furthermore, siderophores produced by these microbes aid in the absorption of Fe3+ from the environment. (Jasim et al., 2015)This mechanism proves beneficial in agriculture by serving as protection against phytopathogens: beneficial organisms limit nutrient availability to pathogens, particularly fungi. The endophytic microbiome found in seeds may include organisms that are highly specialized for these functions, making them vital for seedling establishment and overall plant growth. The production of phytohormones by endophytes underscores their crucial role in regulating plant metabolism and growth. A notable and frequently observed phytohormone synthesized by endophytes is indole-3-acetic acid (IAA). (Jasim et al., 2015)This hormone is essential for initiating root development, promoting plant cell division, elongation, and differentiation. Additionally, IAA supports plant growth and development by enhancing germination of seeds and tubers, improving xylem efficiency, managing vegetative growth processes, stimulating lateral and adventitious root formation, regulating various metabolite syntheses, influencing photosynthesis, and aiding stress resistance. Considering the broad effects of IAA on plants, it stands out as a key feature of seed endophytes. (Xu et al., 2018)The microbial production of IAA occurs via multiple pathways, including the indole-3-acetonitrile (IAN) pathway, the indole-3-acetamide (IAM) pathway, the tryptamine pathway, the indole-3-acetaldoxime pathway, and the indole-3-pyruvate (IPyA) pathway. Ethylene, a naturally occurring plant hormone, is identified as a stress hormone due to its association with stressors like drought, high salinity, waterlogging, and exposure to heavy metals. Ethylene synthesis from methionine involves a three-step process. (Jhuma et al., 2021)Initially, methionine reacts with ATP and water to produce S-adenosyl methionine (SAM). Then, using the enzyme ACC synthase, SAM is converted into 1-aminocyclopropane-1-carboxylic acid (ACC). Finally, ACC is transformed into ethylene through enzymatic activity. However, high levels of ethylene can adversely affect overall plant growth and development, leading to reduced crop yields. The microbial regulation of ethylene production is aided by the conversion of ACC. ACC deaminase takes ACC from plant roots and changes it into ammonia and α-ketobutyrate through deamination and cyclopropane ring breakdown. A decrease in ACC levels results in lower ethylene production, thereby helping alleviate stress in plants. (Jhuma et al., 2021; Xu et al., 2018)Consequently, incorporating bacteria that produce ACC deaminase into plants could provide potential protection against stressful conditions. Several bacterial genera, including Acinetobacter, Achromobacter, Agrobacterium, Alcaligenes, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Ralstonia, Serratia, and Rhizobium, as well as the fungus Penicillium citrinum, have been found to exhibit ACC deaminase activity. Since ethylene can have a significant impact on fruit development and ripening, the negative effects associated with its increased levels in plants could be alleviated by endophytes that produce ACC deaminase. Through the synthesis of ACC deaminase, endophytic organisms play an essential role in regulating plant physiological processes.(De Andrade et al., 2023).

Endophytic Microorganisms as Biocontrol Agents

Biological control refers to a strategy for managing insects, weeds, and diseases through the use of their natural enemies. Harmful organisms, such as pests (insects, parasitic weeds, and pathogens), are significant biotic factors causing considerable losses and damage to agricultural yields. It is vital to control plant pests to ensure the quality and quantity of food, feed, and fiber production. Numerous tactics are currently employed for managing and controlling these plant pests. Major pathogens affecting crops include fungi, bacteria, viruses, and nematodes. The damage inflicted by crop diseases presents a significant threat to food production, with an estimated 27 to 42% of global food losses due to these plant diseases caused by such pathogens, a figure that could have potentially doubled if disease management strategies were not in place.(Gamalero & Glick, 2011)

Endophytic microorganisms produce a diverse range of bioactive substances that can be utilized in agriculture, medicine, and the food industry. While these compounds are mainly generated to benefit their host plants, they possess substantial potential for other applications and are seen as a largely untapped source of pharmaceuticals. The close biological connections and genetic interactions between endophytes and the plants they inhabit likely enhance the production of a wider variety of biological compounds. Recent microbiome research has revealed the impressive biosynthetic abilities of both bacterial and fungal endophytes. This capability is thought to be connected to the evolutionary adaptations of endophytes that help protect plants from pathogens, insects, and herbivores. (Ma et al., 2016)A recent study indicated that organic acids produced by the seed-borne Bacillus amyloliquefaciens can inhibit Fusarium oxysporum and stimulate systemic resistance in tomato plants. This demonstrates the potential of seed endophytes to shield plants through various mechanisms. Numerous investigations have demonstrated that endophytes are vital in managing various plant diseases by generating different secondary metabolites. Endophytic fungi from Nothapodytes foetida, known for producing camptothecin, have also been found to exhibit antifungal properties. The endophytic fungus Pestalotiopsis microspora produces ambuic acid, an antifungal and anti-oomycete compound effective against several Fusarium species and Pythium ultimum. Moreover, endophytic species Acremonium sp. and Paraconiothyrium sp., isolated from Zingiber officinale Rosc., show considerable antifungal activity against the soft rot pathogen Pythium myriotylum due to their production of gliotoxin and danthron.(Vijayabharathi et al., 2016) In addition to these compounds, numerous other biomolecules, such as hypericin, podophyllotoxin, tyrosol, and vinblastine, have been discovered in endophytic fungi that may have applications in pharmaceuticals and agriculture. Furthermore, endophytic Pseudomonas aeruginosa sourced from Zingiber officinale is reported to produce antifungal agents, particularly phenazine-1-carboxylic acid, providing protection to the rhizome from diseases like soft rot caused by Pythium myriotylum. Endophytic strains of Bacillus and Pseudomonas have also demonstrated antagonistic properties against F. oxysporum f. sp. lycopersici (Fol.), the pathogen responsible for tomato wilt. Additionally, volatile antifungal compounds with biocontrol characteristics have been found in endophytic Enterobacter strains derived from rice. Therefore, the identification and characterization of a broad spectrum of endophytes could enhance the formulation of bio-based solutions aimed at tackling agricultural issues while decreasing reliance on agrochemicals.(Ongaga et al., 2025).

Conclusion & Future Prospects

Plant & microbe interactions offer numerous benefits in various agricultural settings. Microorganisms are found extensively in nature and are primarily associated with plants. The relationship between plants and their endophytes is typically regarded as advantageous, playing a significant role in the host plant's physiology and improving its overall health by fostering growth, development, and resilience against a range of biotic and abiotic stress. These relationships are vital for agricultural sustainability, as they provide eco-friendly options for enhancing crop yield and quality while decreasing dependency on harmful chemical fertilizers. Exploring these plant-microbe interactions helps us comprehend natural processes that influence our lives and may lead to sustainable resources, minimized environmental impact, and effective pollution management. Growing concerns about health and environmental threats posed by agrochemicals necessitate the search for alternatives to conventional agricultural practices. Endophytic microorganisms have attracted considerable attention for their ability to enhance plant growth and boost resistance to diseases, thereby protecting plants from both biotic and abiotic pressures. The advantageous endophytic microbiome can be transmitted through seeds to future generations. By investigating the biosynthetic potential of previously identified endophytes, a range of biochemical possibilities with possible agricultural applications can be expected from these microorganisms.

There are still some gaps that must be addressed. One crucial area of research that need to be carried out in the future is the use of new tools and approaches of biotechnology for the investigation of diversity and functionality of endophytic microorganisms within microbiome. Additionally, research into looking for the whole endomicrobiome in plant tissues may reveal new endophytic microorganisms with potent traits and the goal of expanding crops permits further exploitation. Studying endomicrobiome in respective of genomics, proteomics and transcriptional properties requires the use of new biotechnologicals tools and approaches. Endophytic microorganisms extended organic products from various ecological regions. In order to get around known environmental issues, it is also necessary to screen out the potent secondary metabolites that can be used directly in this area.

References

1. Agrawal, S., & Bhatt, A. (2023). Microbial Endophytes: Emerging Trends and Biotechnological Applications. Current Microbiology, 80(6), 184.
2. Andrade, L. A. D., Sales, L. R., & Salles, J. F. (2023). Plant Growth-Promoting Rhizobacteria for Sustainable Agricultural Production. Microorganisms, 11(4), 957.
3. Babalola, O. O., & Adedayo, A. A. (2023). Endosphere microbial communities and plant nutrient acquisition toward sustainable agriculture. Emerging Topics in Life Sciences, 7(5), 765–777.
4. Brader, G., Trognitz, F., & Mitter, B. (2017). Ecology and Genomic Insights into Plant-Pathogenic and Plant-Nonpathogenic Endophytes. Annual Review of Phytopathology, 55, 61–85.
5. Das, D., Sharma, P. L., & Kumar, S. (2025). Harnessing endophytes: innovative strategies for sustainable agricultural practices. Discover Bacteria, 5(1), 1–15.
6. Eid, A. M., Hassan, S. E., & El-Komy, H. M. (2019). Role of Endophytes in Plant Health and Abiotic Stress Management. In Plant Stress Physiology (pp. 121–145). IntechOpen.
7. Eid, A. M., Salem, S. S., & Hassan, S. E. (2021). Harnessing Bacterial Endophytes for Promotion of Plant Growth and Biotechnological Applications: An Overview. Plants, 10(5), 960.
8. Eid, A. M., Salem, S. S., & Hassan, S. E. (2021). Harnessing Bacterial Endophytes for Promotion of Plant Growth and Biotechnological Applications: An Overview. Plants, 10(5), 960.
9. Elsheikh, E. A. E., Saadoun, I., & El-Komy, H. M. A. (2021). Role of Endophytes and Rhizosphere Microbes in Promoting the Invasion of Exotic Plants in Arid and Semi-Arid Areas: A Review. Sustainability, 13(21), 11848.
10. Firáková, S., Šturdíková, M., & Mlynarčík, D. (2007). Bioactive secondary metabolites produced by microorganisms associated with plants. Biologia, 62(3), 251–257.
11. Frank, A. C., Saldierna Guzmán, J. P., & O'Toole, G. A. (2017). Transmission of Bacterial Endophytes. Microorganisms, 5(4), 78.
12. Gaiero, J. R., Best, A. S., & Peñuelas, J. (2013). Inside the root microbiome: Bacterial root endophytes and plant growth promotion. American Journal of Botany, 100(9), 1738–1750.
13. Gamalero, E., & Glick, B. R. (2015). Mechanisms Used by Plant Growth-Promoting Bacteria. The Journal of Plant Nutrition and Soil Science, 178(5), 785–794.
14. Gamalero, E., Lingua, G., & D'Amico, S. (2020). Screening of Bacterial Endophytes Able to Promote Plant Growth and Increase Salinity Tolerance. Applied Sciences, 10(16), 5585.
15. Ghosh, S., Bhagwat, T., & Glick, B. R. (2020). Endophytic Microbiomes and Their Plant Growth-Promoting Attributes for Plant Health. In Plant Microbiome: A Boon for Sustainable Agriculture (pp. 1–25). Springer.

16. Godara, H., & Ramakrishna, W. (2022). Endophytes as nature's gift to plants to combat abiotic stresses. Letters in Applied Microbiology, 75(6), 1111–1121.
17. Guha, T., & Biswas, S. M. (2024). Recent progress in the role of seed endophytic bacteria as plant growth-promoting microorganisms and biocontrol agents. World Journal of Microbiology & Biotechnology, 40(5), 118.
18. Jasim, B., Radhakrishnan, E. K., & Pradeep, A. S. (2015). Effect of endophytic Bacillus sp. from selected medicinal plants on growth promotion and diosgenin production in Trigonella foenum-graecum. Plant Cell, Tissue and Organ Culture (PCTOC), 121(2), 263–272.
19. Jha, P., Panwar, J., & Dhand, R. (2018). Mechanistic insights on plant root colonization by bacterial endophytes: a symbiotic relationship for sustainable agriculture. Environmental Sustainability, 1(1), 1–12.
20. Jhuma, T. A., Sultana, S., & Biswas, S. (2021). Isolation of Endophytic Salt-Tolerant Plant Growth-Promoting Rhizobacteria From Oryza sativa and Evaluation of Their Plant Growth-Promoting Traits Under Salinity Stress Condition. Frontiers in Sustainable Food Systems, 5, 689033.
21. Kandel, S., Joubert, P., & Peñuelas, J. (2017). Bacterial Endophyte Colonization and Distribution within Plants. Microorganisms, 5(4), 77.
22. Kar, S., Kumar, S., Kar, G., Kar, S., & Bhardwaj, A. K. (2023). Endophytic Alkalotolerant Plant Growth-Promoting Bacteria Render Maize (Zea mays L.) Growth Under Alkaline Stress. Current Microbiology, 80(12), 374.
23. Kumar, V., & Nautiyal, C. S. (2022). Plant Abiotic and Biotic Stress Alleviation: From an Endophytic Microbial Perspective. Current Microbiology, 79(9), 291.
24. Kushwaha, P., Bhardwaj, A. K., Sharma, M., & Singh, P. (2020). Bacterial endophyte mediated plant tolerance to salinity: growth responses and mechanisms of action. World Journal of Microbiology and Biotechnology, 36(1), 16.
25. Langner Dos Santos, M., Knaak, N., & Vizzotto, M. (2011). Benefits Associated with the Interaction of Endophytic Bacteria and Plants. Plant Growth Regulation, 63(3), 227–234.
26. Li, E., Jiang, H., & Liang, W. (2021). Rapid evolution of bacterial mutualism in the plant rhizosphere. Nature Communications, 12(1), 3843.
27. Ma, Y., Freitas, H., & Nunes, V. (2011). Biochemical and Molecular Mechanisms of Plant-Microbe-Metal Interactions: Relevance for Phytoremediation. Frontiers in Microbiology, 2, 230.
28. Mei, C., & Flinn, B. (2010). The Use of Beneficial Microbial Endophytes for Plant Biomass and Stress Tolerance Improvement. Recent Patents on Biotechnology, 4(1), 8–24.
29. Montesinos, E. (2003). Plant-associated microorganisms: a view from the scope of microbiology. International Microbiology, 6(3), 1–3.
30. Morsy, M., Cleckler, B., & Glick, B. R. (2020). Fungal Endophytes Promote Tomato Growth and Enhance Drought and Salt Tolerance. Plants (Basel, Switzerland), 9(7), 882.
31. Munir, N., Radicetti, E., & Ali, S. (2022). Mechanisms and Strategies of Plant Microbiome Interactions to Mitigate Abiotic Stresses. Agronomy, 12(8), 1957.
32. Narayanan, M., & Glick, B. R. (2022). Mechanisms Used by Plant Growth-Promoting Bacteria. In Plant Microbiome: A Boon for Sustainable Agriculture (pp. 1-17). Springer.
33. Negi, R., Sharma, B., & Shrivastava, S. (2023). Plant endophytes: unveiling hidden applications toward agro-environment sustainability. Folia Microbiologica, 68(5), 455–468.

34. Ongaga, E. G., Muli, J. K., & Ngetich, J. K. (2025). Endophytic Microflora of Crotalaria: Their Diversity and Role in Plant Growth Promotion. Current Microbiology, 82(3), 75.
35. Pathak, P., Kumar, A., & Gupta, D. (2022). Plant-Endophyte Interaction during Biotic Stress Management. Plants, 11(17), 2321.
36. Ryan RP, Germaine K, Franks A, Ryan DJ, Dowling DN. Bacterial endophytes: recent developments and applications. FEMS Microbiol Lett. 2008 Jan;278(1):1-9. doi: 10.1111/j.1574-6968.2007.00918.x. Epub 2007 Nov 21. PMID: 18034833.
37. Saikkonen, K., Faeth, S. H., & Helander, M. (1998). FUNGAL ENDOPHYTES: A Continuum of Interactions with Host Plants. Annual Review of Ecology and Systematics, 29, 319–343.
38. Shahzad, R., Lee, I.-J., & Ma, Y. (2018). What Is There in Seeds? Vertically Transmitted Endophytic Resources for Sustainable Improvement in Plant Growth. Frontiers in Plant Science, 9, 344.
39. Singh, L. P., Gill, S. S., & Tuteja, N. (2011). Unraveling the role of fungal symbionts in plant abiotic stress tolerance. Plant Signaling & Behavior, 6(2), 241–245.
40. Singh, S., Dhimmar, A., & Mishra, A. (2021). Biodiversity and antimicrobial potential of bacterial endophytes from halophyte Salicornia brachiata. Antonie van Leeuwenhoek, 114(3), 329–343.
41. Strobel, G. A., & Daisy, B. (2003). Bioprospecting for microbial endophytes. Microbiological Reviews, 67(1), 143-162.
42. Tufail, M. A., Chibani, C. M., Khan, S. A., & Bawa, A. (2022). Endophytic bacteria performs better than endophytic fungi in improving plant growth under drought stress: A meta-comparison spanning 12 years (2010-2021). Physiologia Plantarum, 174(5), e13824.
43. Vasileva, E. N., Zhukov, V. A., & Belyaeva, G. V. (2019). Endophytic microorganisms in fundamental research and agriculture. Ecological Genetics, 17(1), 3–14.
44. Verma, A., Parray, J. A., & Khan, A. (2022). Fungal Endophytes to Combat Biotic and Abiotic Stresses for Climate-Smart and Sustainable Agriculture. Frontiers in Plant Science, 13, 858599.
45. Vijayabharathi, R., Gopalakrishnan, S., & Nithya, P. (2016). A Renaissance in Plant Growth-Promoting and Biocontrol Agents by Endophytes. Journal of Applied Microbiology, 121(3), 633-644.
46. Wang, Y.-L., & Zhang, H.-B. (2023). Assembly and Function of Seed Endophytes in Response to Environmental Stress. Journal of Microbiology and Biotechnology, 33(5), 651–662.
47. Watts, D., Zaferanloo, B., & Loo, B. (2023). Endophytes in Agriculture: Potential to Improve Yields and Tolerances of Agricultural Crops. Microorganisms, 11(5), 1176.
48. Wippel, K. (2023). Plant and microbial features governing an endophytic lifestyle. Current Opinion in Plant Biology, 75, 102425.
49. Wu, W., Liu, S., & Li, Z. (2021). Beneficial Relationships Between Endophytic Bacteria and Medicinal Plants. Frontiers in Plant Science, 12, 666752.
50. Xu, L., Wu, C., & Zhang, H. (2018). Role of Phytohormones in Piriformospora indica-Induced Growth Promotion and Stress Tolerance in Plants: More Questions Than Answers. Frontiers in Microbiology, 9, 1582.
51. Zotchev, S. B. (2024). Fungal endophytes: A promising source of novel bioactive compounds. Journal of Antibiotics, 77(1), 1-10.