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Beneficial Endophytic Bacteria in Plants: Their Mechanisms, Diversity, Host Specificity, and Genetic Characteristics

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Abstract

Endophytic bacteria are microorganisms that reside within plant tissues without causing harm. These bacteria play a crucial role in enhancing plant growth and resilience under both normal and stressful conditions. They achieve this by improving nutrient uptake, modulating plant hormones, and protecting plants from pathogens and pests. Endophytic bacteria colonize the plant interior through a series of complex interactions and exhibit remarkable diversity influenced by plant species, environmental factors, and bacterial traits. Their ability to promote plant growth makes them valuable for sustainable agriculture as bio fertilizers and bio pesticides. This review explores the mechanisms of plant growth promotion, the diversity of endophytic bacteria in agriculture. Bacteria, their host specificity, and the genetic determinants involved in their interactions with plants. It also highlights the challenges and future directions for utilizing these bacteria. This also includes about wild plants as a source of various endophytic bacteria and innovative approaches moreover in this article we also discuss about gene expressed in planta and their challenges.

Key words: Endophytic bacteria, Colonization, Plant tissues, Wild plant, Environmental factor, Plant growth promotion, Sustainable agriculture

Plants interact with a variety of microorganisms in their environment, forming associations that are essential for their survival and growth. Among these, endophytic bacteria are particularly significant. These bacteria live inside plant tissues, including roots, stems, leaves, and seeds, without causing any harm [1]. Endophytic bacteria are particularly significant because they inhabit the internal tissues of plants—such as roots, stems, leaves, and even seeds without causing any harm to their host. Unlike rhizosphere or epiphytic bacteria, endophytes inhabit the plant interior, providing a stable ecological niche that shields them from environmental fluctuations. Plants maintain complex and dynamic relationships with a wide range of microorganisms in their surrounding environment, many of which play crucial roles in promoting plant health and productivity [2]. Among these beneficial microorganisms, endophytic bacteria hold special importance due to their unique ability to reside within plant tissues such as roots, stems, leaves, and even seeds without eliciting any disease symptoms or visible damage. Unlike rhizospheric bacteria that colonize the soil region near roots or epiphytic bacteria that live on plant surfaces, endophytes occupy an internal and protected niche within the plant body. This internal colonization not only ensures the bacteria's survival by protecting them from harsh external conditions like temperature fluctuations and desiccation but also allows them to engage in close biochemical interactions with the host [3]. Through these interactions, endophytic bacteria can enhance nutrient acquisition, produce phytohormones, improve stress tolerance, and provide resistance against pathogens, thereby contributing significantly to the plant's overall growth, resilience, and ecological adaptability [4].

Endophytic bacteria are considered a specialized group of plant growth-promoting rhizobacteria (PGPR) that have evolved the ability to invade plant tissues. They enhance plant growth by improving nutrient availability, producing growth hormones, and protecting plants from biotic and abiotic stresses [5]. This review develops into the mechanisms by which endophytic bacteria benefit plants, their diversity, and their potential applications in agriculture. As we observe in almost all plants Endophytic bacteria are present and have been isolated from different tissues of various plants, such as wheat, maize, banana, soya bean, cucumber, onion and cauliflower [6]. These bacteria commonly found in plant tissues and are belong to the genera *Enterobacter*, *Arthrobacter*, *Bacillus*, *Flavobacterium*, *Burkholderia*, *Pseudomonas*, *Serratia*, *Stenotrophomonas*, *Micrococcus*, *Pantoea*, *Microbacterium*, *Klebsiella* and *Herbaspirillum* [7].

Endophytic bacteria constitute a distinct and highly specialized class within the broader group of plant growth-promoting rhizobacteria, notable for their unique evolutionary adaptation that enables them to penetrate, colonize, and persist within the internal tissues of plants such as roots, stems, leaves, and seeds without inducing any pathogenic effects. This symbiotic lifestyle reflects a finely balanced interaction between host and microbe, where the bacteria gain protection and nutrients from the plant's internal environment, while the host benefits from enhanced growth and stress resilience [8]. Unlike surface-dwelling or rhizospheric microorganisms,

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endophytic bacteria establish intimate associations at the cellular and molecular levels, often communicating through chemical signaling to maintain a harmonious relationship. Their non-pathogenic nature indicates a co-evolutionary refinement, allowing them to bypass plant defense mechanisms and contribute beneficially through mechanisms like nutrient mobilization, hormone production, and pathogen suppression. Thus, endophytic bacteria embody a sophisticated form of mutualism that underscores their evolutionary success and ecological significance in promoting sustainable plant growth and health [9]. Their presence contributes significantly to plant vitality through multiple synergistic mechanisms, including enhancing nutrient uptake particularly nitrogen, phosphorus, and iron producing essential phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, and mitigating both biotic stresses (caused by pathogens) and abiotic stresses (such as drought, salinity, and heavy metal toxicity) [10]. The review highlights not only the functional diversity of these bacteria but also their wide distribution across various plant species, underscoring their ecological ubiquity and adaptability. Endophytic bacteria have been successfully isolated from numerous crop plants, including wheat, maize, banana, soybean, cucumber, onion, and cauliflower, reflecting their integral role in maintaining plant health across different ecosystems. Their multifaceted contributions position them as promising bioinoculants for sustainable agriculture, where they can serve as eco-friendly alternatives to chemical fertilizers and pesticides, thereby promoting both productivity and environmental safety.

Colonization of plants by endophytic bacteria

Endophytic bacteria also considered as a small set of rhizospheric bacteria [11-12]. However, if we it compared to rhizo bacteria, its growth has an advantage over rhizosphere growth. Endophytic bacteria are often regarded as a specialized subset of rhizospheric bacteria that have evolved the unique capacity to move beyond the rhizosphere the soil region influenced by root exudates and establish themselves within the internal tissues of plants. While both groups share a common ecological origin and many functional traits related to plant growth promotion, endophytic bacteria differ in their ability to cross the plant’s physical and biochemical barriers, such as the epidermis and cortex, to inhabit the internal cellular spaces without causing harm. This transition from external to internal colonization represents a significant evolutionary advancement, allowing endophytes to maintain a more intimate and stable association with the host plant, sheltered from environmental fluctuations and microbial competition in the soil. Despite their reduced diversity compared to the broader rhizospheric population, endophytic bacteria play disproportionately important roles in enhancing nutrient uptake, synthesizing growth-regulating compounds, and improving plant tolerance to stress. Their origin from the rhizosphere underscores the ecological continuum between soil and plant microbiomes, highlighting how environmental interactions can drive microbial specialization and co-adaptation with plant hosts. Endophytic bacteria living inside plant tissues that allows it to be in close contact with the plant host to exert a direct beneficial effect in return for its consistent supply of nutrients. In fact, these bacteria represent a class of specialized rhizo bacteria and have the ability to invade plant roots after establishing a rhizospheric population [13].

Bacterial colonization within plant tissues is a complex and highly regulated process that is largely determined by a diverse array of bacterial traits that enable successful attachment, invasion, and persistence within the host. These traits include motility mechanisms such as flagella, which facilitate movement toward root exudates through chemotaxis; the production of extracellular polysaccharides (EPS) that aid in adhesion and biofilm formation on root surfaces; and the secretion of cell wall–degrading enzymes like cellulases and pectinases, which help bacteria penetrate plant tissues without triggering strong defensive responses [14]. Additionally, bacterial signaling molecules such as quorum-sensing compounds regulate population density and coordinate colonization behavior, ensuring optimal interaction with host cells. The expression of genes responsible for nitrogen fixation, siderophore production, and phytohormone synthesis further supports the establishment of mutualistic relationships by improving plant nutrition and growth [15]. Moreover, the ability to modulate plant immune responses through the release of effector proteins or antioxidant enzymes allows bacteria to evade plant defenses and maintain a stable internal niche. Collectively, these physiological, biochemical, and molecular traits define the efficiency and specificity of bacterial colonization, shaping the success of plant-microbe associations and their overall impact on plant health and productivity. These characteristics are collectively known as colonization traits and control the overall process of plant colonization. This process involves intricate communication between the two organisms. It typically begins at the roots and depends on the endophytic bacteria detecting specific compounds released in the root exudates [16-17].

Endophytic bacteria colonize plants through a sequential process that begins in the rhizosphere, progresses to the rhizoplane (root surface), and finally leads to the colonization of the plant interior. Endophytic bacteria primarily enter plants through the root zone but can also utilize aerial parts such as stems, leaves, flowers, and cotyledons as entry points. Once inside the roots, they can systemically infect adjacent plant tissues [18].

Rhizosphere colonization

The rhizosphere, the soil region surrounding plant roots, is the initial site of bacterial colonization. Endophytic bacteria compete with other microorganisms for nutrients and space in this highly competitive environment. Traits such as motility, polysaccharide production, and chemotaxis enable bacteria to colonize the rhizosphere effectively. For successful colonization, bacteria must metabolically adapt to the nutrients available in plant root exudates. Matilla *et al*. [19] demonstrated this in Pseudomonas putida KT2440 colonizing the corn rhizosphere, where genes related to metabolism and oxidative stress were upregulated. Their rhizosphere colonization is a tough task for the endophytic bacteria to occupy these spaces and get various nutrients [20]. Only bacteria who are, either beneficial or pathogenic to different plants, that can competitively colonize plant rhizosphere will sustain in this environment and they also have an effect on plant development.

Root colonization

After establishing themselves in the rhizosphere, endophytic bacteria adhere to root surfaces and penetrate the plant interior. Entry points include root tips, lateral root emergence sites, and wounds. Bacteria use mechanisms such as twitching motility, secretion of cell-wall degrading enzymes, and quorum sensing to invade plant tissues. This can penetrate the plant tissues. The penetration process may be active or passive into the host. This depends on the type of host. Active penetration can occur through penetration moreover passive penetrations can be achieved by cracks present at root areas, root tips [21].

Systemic colonization

Once inside the roots, endophytic bacteria spread to other parts of the plant, including stems and leaves. This systemic colonization is facilitated by bacterial flagella, the plant's transpiration stream, and the secretion of enzymes like cellulases and pectinases. The type of endophytic community of a plant is strongly influenced by the nature of plant host species [22]. Different species of plants growing in the different soil can have different endophytic diversity. Thus, the host plant species strongly governs the type of endophytic bacteria colonizing it.

Diversity of endophytic bacteria

Endophytic bacteria are present in almost all types of plants, both cultivated crops and wild species. Research has identified bacterial endophytes in every plant species examined so far, making plants without these bacteria a rare occurrence in nature [23]. In reality, plants lacking these beneficial bacteria tend to be less capable of resisting harmful plant pathogens and are more vulnerable to environmental stresses [24]. Plants lacking endophytic bacteria are more vulnerable to pathogens and environmental stresses because they miss the protective benefits these microbes provide, such as antimicrobial production, competition with pathogens, induction of plant defense mechanisms, enhanced nutrient uptake, and improved tolerance to abiotic stress.

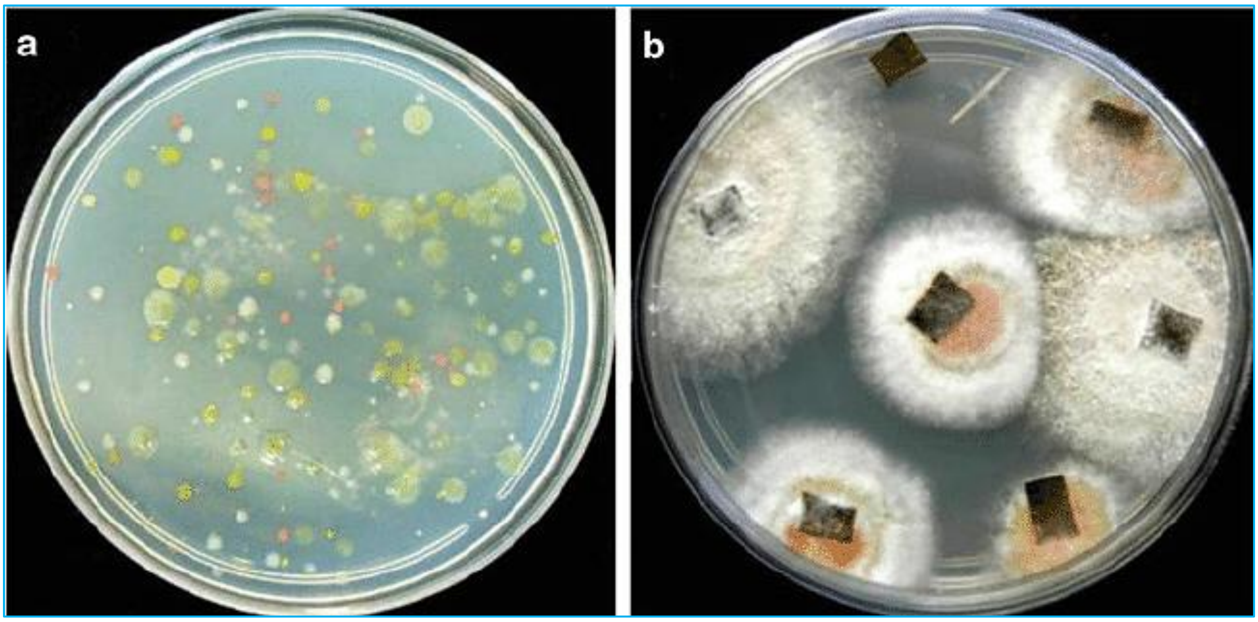

Fig 1 Diversity of culturable endophytic microorganisms isolated from leaf tissue

Their diversity is influenced by several factors:

Plant factors

Host species, genotype, age, and growth stage significantly affect the diversity of endophytes. Different stages of plant growth can influence the diversity of endophytic bacteria, with stages having greater nutrient availability generally exhibiting higher bacterial diversity [25]. The diversity of endophytic bacteria within plants is largely shaped by various plant-related factors, including host species, genotype, age, and developmental stage, all of which create distinct ecological and biochemical niches that determine which microorganisms can successfully colonize and persist. Each plant species and genotype possesses unique physiological traits, metabolic profiles, and chemical compositions such as variations in secondary metabolites, root exudates, and tissue structures that influence bacterial selection and compatibility. Younger plants or those in active growth phases typically offer more nutrient-rich environments, exuding higher levels of sugars, amino acids, and organic acids, which attract a broader range of bacterial species and support greater microbial diversity. Conversely, as plants mature, structural changes in tissues and shifts in nutrient allocation may reduce the abundance or alter the composition of endophytic populations [26]. This dynamic relationship suggests that endophytic bacterial communities are not static but evolve in response to the host's ontogeny, reflecting an intricate interplay between plant physiology and microbial adaptability that ultimately impacts plant health and ecological function.

Interestingly, the type of soil in which a plant is grown can influence the composition of its endophytic bacterial community. As a result, the same plant cultivar cultivated in various agricultural soils may harbour distinctly different endophytic bacteria. For instance, Hossain *et al.* [27] observed notable variations in the diversity of endophytic bacteria in a peanut cultivar grown across different fields. Similarly, Rashid *et al.* [28] isolated a variety of endophytic bacterial types by cultivating a single tomato cultivar in 15 different agricultural soils. Together, these studies suggest that the diversity of endophytes is largely shaped by the varying characteristics of soil environments.

Environmental factors

Moreover, climatic factors also affect the endophytic communities within a plant species. For instance, Qian *et al.* [29] reported that climate variations significantly changed the abundance and makeup of endophytic bacteria in leaf tissues. Soil type, climate, and geographical location play a crucial role in shaping endophytic communities.

Methodological factors

The techniques used to isolate and study endophytes, such as culture-based or culture-independent methods, can influence the observed diversity. Proteobacteria, Actinobacteria, Firmicutes, and Bacteroidetes are the most commonly found bacterial phyla in plants. Genera such as Bacillus, Pseudomonas, Burkholderia, and Micro bacterium are frequently isolated from various plant species [30].

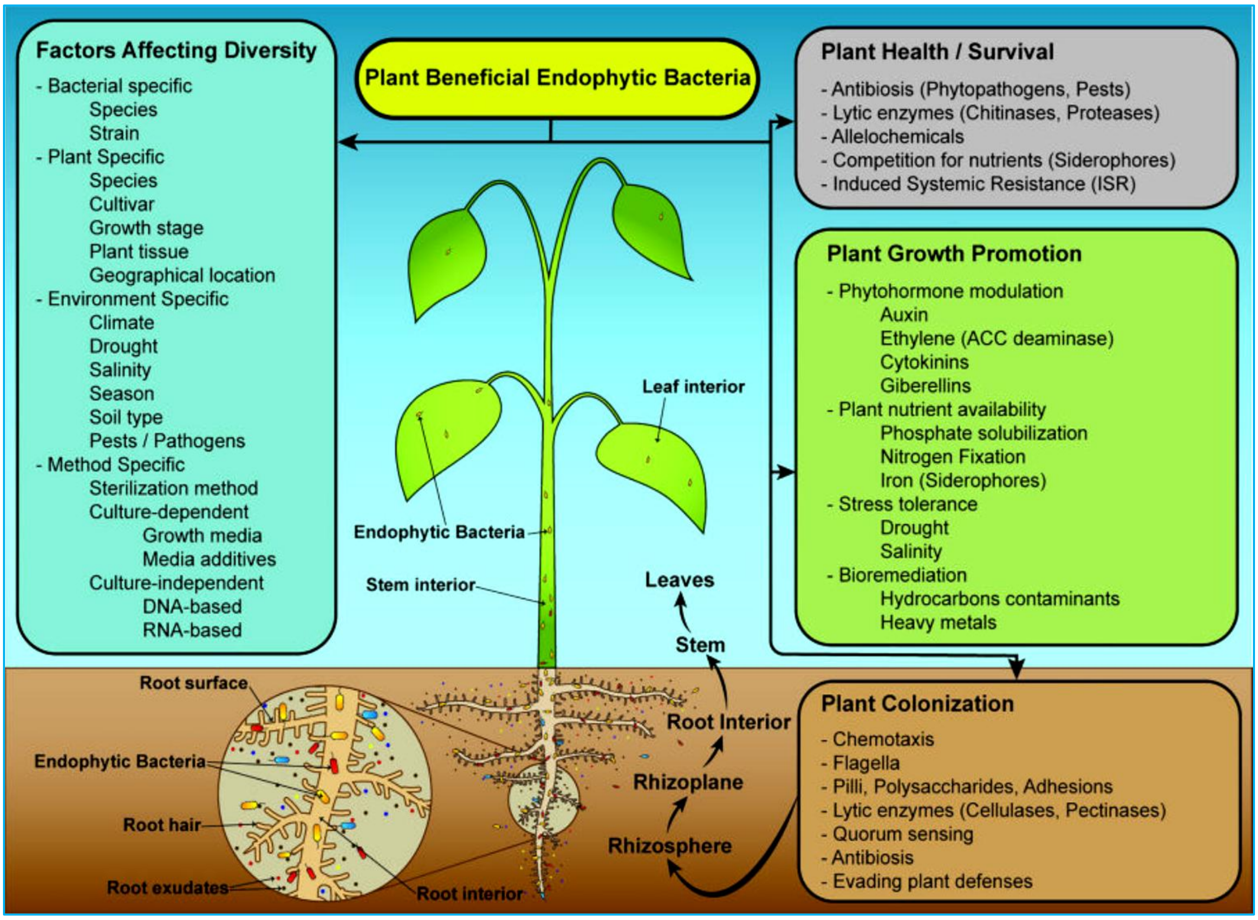

Fig 2 Mechanisms of plant growth promotion, colonization, and factors affecting diversity of endophytic bacteria in host plant

Table 1 Representative plants and their associated endophytic bacterial genera

Plants	Endophytic bacterial genera
Alfalfa	*Bacillus, Erwinia, Microbacterium, Pseudomonas, Salmonella*
Banana	*Azospirillum, Burkholderia, Citrobacter, Herbaspirillum, Klebsiella*
Black pepper	*Arthrobacter, Bacillus, Curtobacterium, Micrococcus, Pseudomonas, Serratia*
Carrot	*Agrobacterium, Bacillus, Klebsiella, Pseudomonas, Rhizobium, Salmonella, Staphylococcus*
Clover	*Agrobacterium, Bacillus, Methylobacterium, Pseudomonas, Rhizobium*
Cotton	*Bacillus, Burkholderia, Clavibacter, Erwinia, Phyllobacterium, Pseudomonas*
Maize	*Achromobacter, Agrobacterium, Arthrobacter, Bacillus, Burkholderia, Corynebacterium*
Pineapple	*Azospirillum, Burkholderia*
Potato	*Acidovorax, Acinetobacter, Actinomyces, Agrobacterium, Alcaligenes, Arthrobacter*
Radish	*Proteobacteria, Salmonella*
Red clover	*Acidovorax, Agrobacterium, Arthrobacter, Bacillus, Bordetella, Cellulomonas, Comamonas*
Rice (wild and cultivated)	*Agrobacterium, Azoarcus, Azorhizobium, Azospirillum, Bacillus, Bradyrhizobium*
Soybean	*Erwinia, Agrobacterium, Pseudomonas, Klebsiella, Enterobacter, Pantoea, Bacillus*
Sugar cane	*Acetobacter, Gluconacetobacter, Herbaspirillum, Klebsiella*
Tomato	*Brevibacillus, Escherichia, Pseudomonas, Salmonella*

Mechanisms of plant growth promotion

Nitrogen fixation

Endophytic bacteria like Azoarcus and Azospirillum convert atmospheric nitrogen into a form usable by plants. Nitrogen is the most crucial and often limiting macronutrient for plant growth and development. Although nitrogen is abundant in the atmosphere making up about 78% of atmospheric gases primarily in its diatomic form (N_2) plants cannot directly utilize this form. Instead, they absorb nitrogen mainly as nitrate (NO_3^-), ammonium (NH_4^+), or, in some cases, amino acids depending on soil conditions. Consequently, despite the vast availability of atmospheric nitrogen, the amount accessible to plants in agricultural soils is typically limited. To meet the high nitrogen demand in agriculture, synthetic nitrogen fertilizers such as ammonia, urea, and ammonium nitrate are widely used. While these fertilizers are essential for supporting increasing food production, their long-term application can lead to significant environmental issues. These include (i) elevated emissions of nitrous oxide (N_2O), a potent greenhouse gas; (ii) nitrate build up in groundwater, which poses health risks to humans; (iii) the decline of certain plant species; (iv) encouragement of invasive grass species; and (v) nutrient imbalances and eutrophication, which can deplete vital soil minerals like magnesium, calcium, and phosphorus. This depletion may also result in the increase of harmful elements such as aluminium, which adversely affect plants, fish, and other aquatic life [31].

Phosphorus solubilization

These bacteria release organic acids and enzymes to solubilize insoluble phosphorus in the soil. The binding of phosphorus by cations to form mineral salts reduces fertilization efficiency and crop profitability, leading to economic losses and environmental concerns such as soil quality degradation [32]. Prolonged and excessive use of phosphate fertilizers often results in elevated phosphorus levels in water bodies due to the runoff of phosphorus-rich soil particles into lakes and surface waters [33]. Furthermore, many commercially available phosphorus fertilizers contain harmful elements including lead (Pb), fluorine (F), arsenic (As), cadmium (Cd), mercury (Hg), and chromium (Cr), as well as radioactive substances like Ra-226, Th-232, Pb-210, Po-210, and U-238 [34].

Hormone production and modulation

Phytohormones, also known as plant hormones, play a central role in regulating plant growth, development, and responses to environmental stresses, and their production and modulation by endophytic bacteria form a vital component of plant-microbe interactions [35]. These hormones are broadly categorized into five major groups auxins, cytokinins, gibberellins, abscisic acid, and ethylene along with other important signaling molecules such as brassinosteroids, jasmonic acid, and salicylates [36]. Among these, auxins, particularly indole-3-acetic acid (IAA), stand out as the most influential in stimulating plant growth processes including cell division, elongation, and differentiation. IAA also orchestrates vital physiological functions such as tropic responses, root initiation, and the development of lateral roots and root hairs, thereby expanding the root surface area and enhancing the plant's ability to absorb water and nutrients efficiently [37]. Meanwhile, cytokinins and gibberellins complement auxin activity by promoting shoot elongation, leaf expansion, and overall biomass accumulation. On the other hand, stress-related hormones like abscisic acid, ethylene, jasmonic acid, and salicylates modulate plant defense and resilience, triggering systemic resistance mechanisms that help plants withstand abiotic challenges such as drought and salinity, as well as biotic stresses from pathogens [38]. Through the synthesis and regulation of these phytohormones, endophytic bacteria act as natural biostimulants, finely tuning the hormonal balance within the host plant to optimize both growth and stress adaptation in a sustainable and ecologically beneficial manner [39].

Pathogen suppression

Endophytic bacteria protect plants from pathogens by producing antibiotics, hydrolytic enzymes, and antimicrobial compounds. They also induce systemic resistance in plants, priming their defence mechanisms against future attacks. Endophytic bacteria play a pivotal role in protecting plants from pathogenic infections through multiple, well-coordinated biochemical and physiological mechanisms that collectively enhance plant immunity and resilience [40]. One of their primary modes of action involves the production of antibiotics and antimicrobial compounds such as phenazines, pyoluteorin, and hydrogen cyanide which directly inhibit the growth of phytopathogens in the plant's internal and surrounding environments. Additionally, many endophytes secrete hydrolytic enzymes like chitinases, glucanases, and proteases that degrade the cell walls of fungi and other harmful microbes, thereby suppressing pathogen proliferation [41]. Beyond direct antagonism, endophytic bacteria also activate the plant's own defense systems through a process known as induced systemic resistance (ISR), which "primes" the host's immune machinery to respond more rapidly and robustly upon pathogen challenge. This involves the upregulation of defense-related genes, increased production of phytoalexins, and strengthening of cell walls, providing long-lasting protection without the need for continuous bacterial presence [42]. Together, these direct and indirect defense strategies make endophytic bacteria vital biological control agents, reducing dependence on chemical pesticides while promoting a sustainable and ecologically balanced approach to crop protection.

Host specificity of endophytic bacteria

The ability of endophytic bacteria to promote plant growth depends on both the plant and bacterial genotypes. While some endophytes are highly specific to their host plants, others have a broad host range. For example, *Burkholderia phytofirmans* PsJN can promote the growth of multiple crops, including wheat, maize, and tomato. This broad host range makes endophytes valuable for agricultural applications [43]. The host specificity of endophytic bacteria reflects the intricate and dynamic relationship between microbial and plant genotypes, determining the compatibility, colonization efficiency, and effectiveness of plant growth promotion. The extent of this specificity varies widely some endophytic bacteria form highly specialized associations limited to particular plant species or genotypes, shaped by co-evolutionary adaptations such as recognition of plant-derived signaling molecules, compatibility with root exudate chemistry, and immune tolerance mechanisms [44]. In contrast, others exhibit a broad host range, demonstrating remarkable adaptability to colonize diverse plant species across different families. A well-known example is *Burkholderia phytofirmans* PsJN, which enhances the growth and stress tolerance of multiple crops including wheat, maize, and tomato, indicating its ability to interact with a wide spectrum of plant hosts through flexible metabolic and signaling pathways. Such generalist endophytes are particularly valuable in sustainable agriculture, as they can be developed into bioinoculants or biofertilizers applicable to varied cropping systems, reducing the need for host-specific microbial formulations [45]. Ultimately, understanding host specificity not only helps identify the genetic and biochemical determinants of successful plant-microbe partnerships but also aids in the strategic utilization of endophytes to improve crop productivity and resilience across diverse agroecosystems.

Challenges and future direction

Despite their potential, the use of endophytic bacteria in agriculture faces challenges. Field results are often inconsistent due to the complex dynamics of plant-microbe interactions. To address this, future research should focus on:

Understanding molecular mechanisms

Advanced techniques like RNA sequencing can reveal the genes and pathways involved in plant-endophyte interactions. Understanding the molecular mechanisms underlying plant-endophyte interactions is crucial for elucidating how these symbiotic relationships influence plant growth, stress tolerance, and overall health [46]. Modern molecular biology tools, particularly high-throughput approaches like RNA sequencing (RNA-seq), have revolutionized this field by enabling comprehensive analysis of gene expression patterns in both plants and their associated endophytic bacteria during colonization and interaction [47].

Through transcriptomic profiling, researchers can identify specific genes and regulatory networks that govern signaling, nutrient exchange, phytohormone modulation, and defense activation. For instance, RNA-seq can reveal how plants upregulate defense-related or stress-response genes in the presence of beneficial endophytes, while simultaneously uncovering bacterial genes responsible for colonization, biofilm formation, or production of growth-promoting compounds. This dual analysis helps map the bidirectional communication that establishes a stable and cooperative association [48-49]. Moreover, integrating RNA-seq data with proteomic and metabolomic studies provides a systems-level understanding of the molecular dialogue between host and microbe. Such insights are essential for developing targeted bioinoculant technologies, optimizing plant–microbe compatibility, and harnessing endophytes for sustainable agricultural innovation [50].

Exploring wild plants

Wild plants, which thrive in harsh environments, may harbor unique endophytes with valuable traits. Exploring wild plants presents an important frontier in the discovery of novel endophytic bacteria, as these plants have naturally adapted to thrive in extreme or resource-limited environments, such as arid soils, saline regions, high altitudes, and nutrient-poor ecosystems [51]. The endophytes residing within such resilient hosts are likely to possess unique physiological and genetic traits that contribute to the plant's survival under stress conditions, including enhanced tolerance to drought, salinity, temperature fluctuations, and pathogen attacks. These microorganisms often produce specialized metabolites, osmoprotectants, and stress-related enzymes that not only support their own survival but also bolster their host's adaptive mechanisms. By isolating and characterizing endophytes from wild plant species, researchers can identify new strains with exceptional abilities to promote crop growth, fix atmospheric nitrogen, solubilize nutrients, or produce bioactive compounds with antimicrobial or antioxidant properties [52]. Such discoveries hold immense potential for sustainable agriculture, as these robust endophytes can be developed into biofertilizers or biostimulants to improve cultivated plant performance under climate stress. Thus, wild plants act as reservoirs of untapped microbial diversity, offering a valuable gateway to enhance agricultural productivity and resilience in the face of global environmental challenges.

Optimizing field applications

Pre-forming plant-endophyte associations under controlled conditions can improve field performance. Optimizing field applications of endophytic bacteria involves strategically establishing effective plant-microbe associations under controlled conditions before field transplantation to ensure consistent and enhanced performance in real agricultural environments [53]. By pre-inoculating plants with selected endophytes in laboratory or greenhouse settings, researchers can facilitate early colonization of roots and internal tissues, allowing beneficial interactions such as improved nutrient uptake, phytohormone regulation, and stress adaptation to become established prior to exposure to variable field conditions [54]. This controlled association enhances plant vigor, promotes faster establishment in soil, and increases resilience to environmental stresses such as drought, salinity, and pathogen attacks. Moreover, pre-conditioning enables the selection of compatible endophyte strains tailored to specific crops and soil types, ensuring stable colonization and sustained activity throughout the growing season. Such proactive integration of endophytes into the plant system minimizes inconsistencies often encountered in field inoculations, where environmental factors can hinder bacterial survival or colonization efficiency [55]. Therefore, pre-forming plant-endophyte partnerships represents a practical and scientifically grounded approach to translating laboratory successes into reliable field-level outcomes, contributing significantly to the development of sustainable and high-performance agricultural practices.

CONCLUSION

Endophytic bacteria offer a sustainable solution for enhancing crop productivity and resilience. By improving nutrient uptake, modulating plant hormones, and protecting against pathogens, these bacteria can reduce the need for chemical fertilizers and pesticides. However, a deeper understanding of their biology and interactions with plants is essential to unlock their full potential. With continued research, endophytic bacteria could revolutionize sustainable agriculture and environmental management. Endophytic bacteria offer great potential in sustainable and environmentally friendly agriculture through their abilities to fix atmospheric nitrogen, solubilize phosphate, produce phytohormones, and suppress plant pathogens and pests. Their application supports plant growth while reducing the need for chemical fertilizers and pesticides. This section provides an overview of technological advancements focused on three major crops: corn, soybean, and sugarcane. Patent publication activity was dominated by China the USA, Canada, and Brazil. Numerous novel bacterial strains have been patented as bioinoculants or biopesticides. These bacterial formulations are primarily designed for seed coating or foliar spraying and are effective in controlling pests and diseases as well as enhancing plant resilience to environmental stresses. Often, they promote growth by producing hormones that regulate or improve the uptake of nutrients.

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