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Review Article

Exploring the Role of Bacterial Endophytes in Enhancing Agricultural Productivity and Ecological Sustainability: A Comprehensive Review

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Abstract

Bacterial endophytes have emerged as key contributors to agricultural productivity and ecological sustainability, particularly in the face of global environmental challenges and the growing demand for sustainable development. These microorganisms support plant health through multiple mechanisms, including the production of bioactive compounds with potential applications in biotechnology and medicine. Acting as natural biocontrol agents, they reduce the reliance on chemical fertilizers and pesticides, thereby promoting eco-friendly farming practices. By enhancing crop resilience, improving pest management, and sustaining agricultural productivity, bacterial endophytes offer promising solutions for environmentally responsible agriculture. Beyond agriculture, their role in sustainable industrial processes has also gained attention. The integration of bacterial endophytes into diverse economic sectors holds the potential to balance ecological stability with human needs. However, much of their potential remains underexplored. Future research should focus on expanding their applications, understanding their mechanisms in greater depth, and evaluating their long-term ecological impacts. This review highlights the remarkable promise of bacterial endophytes as innovative tools for addressing modern challenges while contributing to sustainable and environmentally friendly practices across agriculture, biotechnology, and industry.

Keywords: Endophytes; Plant Growth Promotion; Biofertilizers; Phytoremediation; Industrial Applications

Introduction

The word "endophyte" comes from the Greek words "endon," which means within, and "phyton" meaning plant [1,2]. Microorganisms like bacteria and fungi were included in the definition of endophytes which live in the plant endosphere for all or part of their life cycle without producing any obvious symptoms damage to the host plant. They live asymptomatically in the plant cellular environment and perform specific functions such as synthesis of secondary metabolites or signalling molecules that function as internal and external stimuli during the mutualistic interaction [3,4]. They create a symbiotic connection in which they frequently benefit the plant by boosting growth, strengthening resistance to infections, and promoting tolerance to abiotic challenges such heavy metals, salt, and drought. The host plant provides endophytes with nutrition and a protected habitat in exchange. Endophytic microbes are sources of novel biomolecules for the biochemical and pharmaceutical industries. They are produce biologically active metabolites such as antibiotics, insecticides, antioxidants, plant growth promoters, antimicrobial volatiles, anticancer drugs, and immunosuppressants in agriculture, the pharmaceutical industry, and medicine [5] that mentioned in figure 1. Under adverse situations like nutritional stress, temperature stress, salinity, trace metal stress, or drought, endophytic microorganisms can promote plant development [6]. Moreover, they also play major role in growth and development of plant in contaminated regions by degrading harmful compounds [7].

Figure 1: Prospective biotechnological applications of bacterial endophyte.

Bacterial endophytes

Endophytic bacteria have been classified into 16 phyla, encompassing more than 200 genera. However, the majority of known endophytes belong to three major phyla: Proteobacteria, Actinobacteria, and Firmicutes [8]. Common examples include both Gram-positive and Gram-negative genera such as *Pseudomonas*, *Achromobacter*, *Agrobacterium*, *Xanthomonas*, *Acinetobacter*, *Microbacterium*, *Bacillus*, and *Brevibacterium* [9]. These bacteria are found in a wide range of plant species, indicating that they are associated with nearly all higher plants. The composition and structure of endophytic bacterial communities are shaped by several factors, including Soil biotic and abiotic conditions that influence bacterial survival, Host plant traits that facilitate colonisation, and Microbial characteristics that determine the ability of endophytes to establish, adapt, and compete within plant tissues [10]. Once inside the host, bacterial endophytes penetrate and colonise internal plant tissues, where they utilise organic compounds from the plant for their growth and survival [11]. At the same time, they are able to evade host defence mechanisms, ensuring a successful symbiotic association.

Entry and colonization of bacterial endophyte in plant

The first step in endophytic colonisation is the attachment of bacterial cells to the plant surface. Bacteria located near plant roots are guided toward them by chemotaxis, where they sense and move in response to root exudates. Once they reach the root surface, attachment occurs an essential step for gaining access to entry points such as lateral root emergence sites, wounds, or mechanically damaged areas. The production of exopolysaccharides (EPS) by bacteria plays a key role in this adhesion process. For example, the EPS of *Gluconacetobacter diazotrophicus* Pal5 has been shown to be crucial for its attachment and colonisation of rice roots [12]. Other bacterial structures, such as flagella, fimbriae, and cell surface polysaccharides, also support adhesion to the root surface. After successful attachment to the rhizoplane (root surface), endophytic bacteria search for entry points into the plant's interior. Common entry sites include stomata, hydathodes, lenticels, wounds, and openings formed by the emergence of root hairs or lateral roots [13]. Some bacteria are also capable of penetrating through germination radicles and seed surfaces, establishing early associations with the plant.In addition to natural openings, many endophytic bacteria actively modify plant cell walls to gain entry. They produce cell wall–degrading enzymes such as cellulases, xylanases, pectinases, and endoglucanases, which help them, penetrate and spread throughout plant tissues [14,15]. Therefore, entry into plants can occur via passive routes (through natural cracks and seeds) or active enzymatic degradation, allowing endophytes to establish themselves in a wide range of tissues which mentioned in figure 2.

Bacterial endophytes most commonly inhabit the intercellular spaces of plants, which are rich in carbohydrates, amino acids, and inorganic nutrients [16,17]. These niches provide favourable conditions for their survival. Endophytes have been reported in vari-

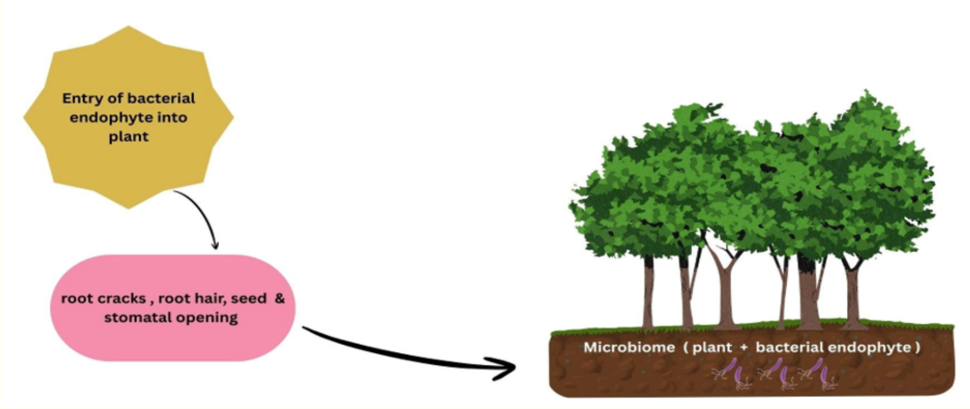

Figure 2: Different routes of entry of bacterial endophyte.

ous plant parts, including roots, stems, leaves, flowers, and seeds [18]. Colonisation can occur locally within specific tissues or systemically throughout the entire plant body. During the early stages of colonisation, endophytes are often detected in root hairs and subsequently in the root cortex [19]. For example, *Burkholderia sp*. strain PsJN has been observed colonising cortical cells, the endodermis, and even the xylem vessels. High levels of colonisation are usually found in primary and secondary roots, root tips, and the bases of lateral roots. From the roots, endophytes may spread to aerial tissues such as stems and leaves, aided by their motility and the secretion of cellulolytic enzymes. In leaves, bacterial endophytes have been identified in substomatal chambers, mesophyll intercellular spaces, and xylem tissues. Colonisation studies using *Burkholderia sp*. strain PsJN, labelled with green fluorescent protein (GFP) and **β-glucuronidase (GUS) staining**, confirmed their presence in the xylem and substomatal chambers of grapevine leaves [20]. Entry into the intracellular environment can occur either through cell wall–degrading enzymes or via a process known as rhizophagy. Rhizophagy is a recently described phenomenon in which plant roots actively attract soil microbes into their cells, where they may be partially digested to obtain nutrients [21]. Interestingly, this process can also increase intracellular reactive oxygen species (ROS) levels, which may help plants, tolerate stresses such as drought, salinity, and heat [22]. The ability of endophytes to persist inside plant cells represents a remarkable adaptation strategy. For instance, studies in switchgrass revealed that certain internal endophytes transition into an L-form (cell wall–deficient state), making them difficult to culture under normal laboratory conditions. This unique adaptation highlights their specialised niche within plant tissues, where competition from other microbes is minimal.

Interaction between plant and bacterial endophyte

Plants and bacterial endophytes interact in multiple ways, and these interactions are not always harmful. In fact, many of them are beneficial, either directly or indirectly, to plant growth and survival [23]. A well-known example is the *Rhizobium–legume* interaction, where both partners adjust their metabolism to support each other. While some endophytic relationships are highly specialized, most are less specific but still help plants grow better under both normal and stressful conditions [24]. Plants release root exudates (a mix of sugars, amino acids, and other compounds) to attract beneficial bacteria. These chemical signals guide bacterial endophytes toward the root surface. Once they reach the roots, bacteria adhere using structures like fimbriae, flagella, polysaccharides, and lipopolysaccharides. For instance, *Rhizobium* species modify their surface polysaccharides when shifting from a free-living state to a symbiotic form [25]. To enter plant tissues, endophytes often secrete cell wall–degrading enzymes such as cellulases, xylanases, pectinases, and endoglucanases. This allows them to penetrate through natural openings (like root hairs, lateral root emergence points, or wounds) or by active mechanisms involving pili, flagella, twitching motility, and quorum sensing [26-28]. Passive entry can also occur through cracks at root tips or injuries caused by other organisms [29]. After entry, bacteria usually colonize the root surface first and then move to internal tissues. They can spread to aerial plant parts (stems, leaves, flowers, seeds, and even xylem vessels) through the transpiration stream [30]. Inside the plant, most endophytes prefer the intercellular spaces, which are rich in nutrients like sugars, amino acids, and minerals. In some cases, they may enter root cells directly through the plasma membrane or participate in rhizophagy, a process where microbes are taken into root cells and partially digested to release nutrients [31]. Thus, Endophytic bacteria can inhabit the intercellular spaces of stems, leaves, seeds, flowers, fruits, and xylem vessels in addition to colonizing roots.

Role of bacterial endophyte in agriculture sustainability

Bacterial endophytes in crop management

The role of bacterial endophytes in crop management is influenced by multiple factors, including plant genetics, developmental stage, environmental conditions, and agricultural practices. Plant genotype directly affects the composition of plant-associated bacteria, as root exudates vary among species and cultivars, thereby shaping rhizobacterial colonization and subsequent endophytic establishment [32]. Similarly, the host plant's stage of development influences bacterial populations; for example, in soybean, endophytic bacterial numbers increase during vegetative growth but decline as the plant enters the reproductive phase [33]. Environmental factors, such as temperature fluctuations and tissue type, also play a significant role in shaping endophyte colonization [34]. Soil, in particular, has been identified as a major determinant of bacterial diversity, as demonstrated by the variation of *Burkholderia cepacia* populations associated with maize roots under different soil conditions [35]. Agronomic management practices, especially the use of agrochemicals, exert a strong influence on crop-associated microbial communities. Studies on transgenic and non-transgenic sugarcane revealed that herbicide application altered endophytic populations, with reduced bacterial density observed in the rhizosphere of transgenic sugarcane treated with the herbicide Imazapyr compared to its non-transgenic counterpart [36]. Glyphosate, the most widely used herbicide in glyphosate-resistant soybean and maize cultivation, also has significant effects on microbial ecology. As a broad-spectrum, systemic herbicide, glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), disrupting aromatic amino acid biosynthesis, leading to growth inhibition and eventual plant death [37]. The adoption of glyphosate-tolerant crops has provided farmers with several advantages, including reduced use of more toxic herbicides, simplified weed management, and comparatively lower soil persistence of residues. Despite these benefits, glyphosate application can alter soil microbial communities [38]. Research in Brazil revealed notable differences in the composition and density of endophytic communities between conventional and glyphosate-tolerant soybean plants. While glyphosate reduced fungal populations in the soil, its effects on bacterial counts were less pronounced. However, glyphosate was found to inhibit microbial activity in different soil types, such as Psament and Oxisol, and repeated applications reduced bio-mineralization, further indicating its influence on soil microbial functions [39]. These findings demonstrate that herbicide use, particularly glyphosate, shapes endophytic communities by selecting strains that can tolerate or metabolize herbicides. This presents an opportunity for the isolation and utilization of endophytes capable of degrading herbicides. Such strains could be applied as inoculants to crops, offering an environmentally friendly alternative to genetic modification for conferring herbicide tolerance. Thus, bacterial endophytes not only play a vital role in crop health and productivity but also represent a promising resource for developing sustainable weed and soil management strategies [40,41].

Contribution of Bacterial endophytes to biodiversity

Bacterial endophytes, which live hidden within plant tissues, play a crucial role in maintaining and enhancing biodiversity [42]. The interaction between endophytes and their host plants is highly complex, yet it significantly influences internal plant processes and contributes to ecological balance [43]. Colonization is determined by both the bacterial endophyte and the host plant, and in some cases, specific microbes form associations with particular plant species. This specificity leads to distinct endophytic communities across different plant hosts, thereby enriching the microbiological diversity within agricultural and natural ecosystems [44]. Beyond their role within plants, endophytes also influence the surrounding soil environment. By producing bioactive compounds in the rhizosphere, they create favourable conditions for beneficial microbes, leading to the development of interconnected soil microbiomes [45]. Such interactions enhance microbial diversity and contribute to healthier and more resilient ecosystems [46]. For example, in grassland ecosystems, endophytes have been shown to positively affect soil microbial diversity, highlighting their broader ecological significance. At higher trophic levels, the impact of bacterial endophytes extends further. Plants supported by endophytes often display improved resistance to diseases and environmental stress, creating stable ecosystems that can sustain herbivores, pollinators, and decomposers [47]. This mutualistic relationship strengthens ecosystem functioning, ensuring balance across multiple levels of biodiversity. Overall, bacterial endophytes contribute to biodiversity by shaping plant-associated microbial populations, influencing soil ecosystems, and supporting ecological interactions across trophic levels. Their role is vital in building resilient, flexible, and diverse agricultural environments. Harnessing these microbial interactions is therefore essential for protecting biodiversity and promoting sustainable farming practices that align with ecological stability [48].

Industrial applications of bacterial endophyte

Bacterial endophytes play a vital role in various industries due to their ability to produce a wide range of metabolites, enzymes, and bioactive compounds. Their remarkable metabolic versatility and adaptability make them valuable resources in agriculture, biotechnology, pharmaceuticals, and environmental management [49]. By harnessing their natural capabilities, endophytes provide sustainable and eco-friendly alternatives to synthetic inputs, contributing to both innovation and environmental sustainability [50]. One of the most significant contributions of bacterial endophytes is in bioremediation, where their exceptional metabolic systems help degrade pollutants and purify contaminated soil and water. They also serve as sources of biofertilizers, biocontrol agents, and growth-promoting metabolites, which enhance crop productivity while reducing reliance on chemical fertilizers and pesticides [51]. For instance, *Bacillus amyloliquefaciens* acts as a biocontrol agent against plant pathogens, while *Bacillus subtilis* produces metabolites that promote plant growth and improve soil health [52,53]. In the pharmaceutical industry, endophytes are recognized as prolific producers of antibiotics and other therapeutic compounds. A classic example is *Streptomyces griseus*, which produces streptomycin, an important antibiotic widely used in medicine. Similarly, *Streptomyces rimosus* produces oxytetracycline, a compound with applications in combating antimicrobial resistance and drug discovery [54]. Such metabolites highlight the importance of endophytes in addressing pressing global health challenges. Beyond agriculture and medicine, bacterial endophytes have diverse applications in biotechnology, food, textiles, cosmetics, and bioenergy shown in figure 3. For example, *Burkholderia phytofirmans* and *Chromobacterium violaceum* produce metabolites with potential use in environmental management and industrial innovation [55]. *Saccharopolyspora spinosa* produces spinosad, a bioinsecticide valuable for sustainable pest control. These examples demonstrate the versatility of endophytes as natural biofactories with wide-ranging industrial benefits. Thus, the diverse functions of bacterial endophytes underscore their potential as key agents of sustainable industrial development. Continued research and careful exploration of their unique traits will enable the creation of innovative solutions across sectors, ensuring long-lasting and environmentally friendly outcomes.

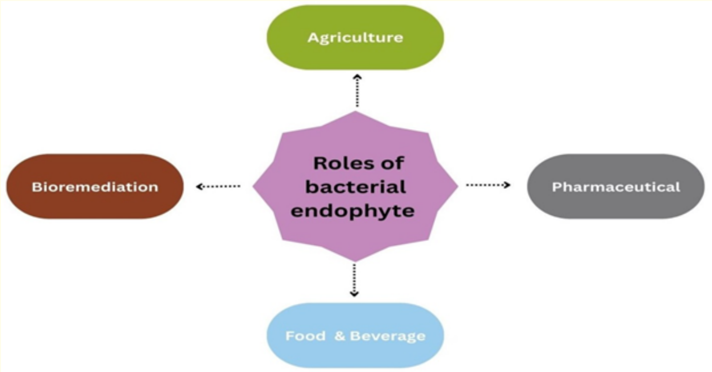

Figure 3: Various applications of bacterial endophyte.

Bacterial endophytes in phytoremediation

Bacterial endophytes have emerged as powerful allies in phytoremediation, offering sustainable solutions to environmental degradation. Phytoremediation, the use of plants and their associated microbes to remove or neutralize pollutants, represents a cost-effective and eco-friendly alternative to conventional methods such as excavation, incineration, and chemical treatments, which are expensive, disruptive, and often generate secondary pollutants [57]. Endophytes enhance the efficiency of this process through their unique metabolic versatility, enabling them to degrade, transform, or completely detoxify a wide range of contaminants [58]. The broad enzymatic capabilities of bacterial endophytes make them particularly valuable in phytoremediation. These microbes can metabolize organic pollutants such as hydrocarbons, pesticides, and industrial chemicals, while also aiding in the sequestration and detoxification of heavy metals. Their polyvalent nature allows them to adapt to diverse contaminant types, positioning them as suitable candidates for multiple remediation strategies [59]. Beyond pollutant degradation, endophytes strengthen the phytoremediation process through their symbiotic interactions with host plants. By producing growth-promoting hormones and defensive compounds, they improve nutrient uptake, stimulate biomass production, and enhance root elongation. This not only accelerates plant growth but also increases the capacity of plants to absorb, immobilize, and transform environmental contaminants [60]. In this way, endophytes act as facilitators, enabling plants to thrive in polluted soils while simultaneously cleaning up damaged ecosystems. Several case studies highlight the effectiveness of endophytes in practical applications. Certain strains have been shown to reduce heavy metal concentrations in contaminated soils by improving host plant tolerance and assisting in metal sequestration. Others demonstrate the ability to degrade persistent organic pollutants, including pesticides and hydrocarbons, expanding their utility in diverse remediation contexts [61]. Therefore, bacterial endophytes represent a promising frontier in phytoremediation research and practice. Their dual role in both pollutant degradation and plant growth promotion positions them as key players in sustainable ecosystem restoration. As scientific knowledge deepens, harnessing these microbial partners will contribute to more effective, eco-friendly strategies for addressing the long-standing challenge of soil, water, and air pollution.

Enhancing agricultural productivity by endophytes

In recent years, increasing attention has been given to bacterial endophytes for their potential role in improving agricultural productivity. These beneficial microorganisms live within plant tissues and contribute directly to plant growth and yield enhancement. Endophytes are valuable partners in sustainable farming as they produce growth-promoting compounds, facilitate nutrient availability, and help plants withstand various stresses. Their applications in agriculture demonstrate significant benefits such as improved crop productivity, nutrient recycling, reduced reliance on chemical fertilizers and pesticides, and enhanced ecological balance [62]. Several bacterial endophytes have been recognized as effective alternatives to synthetic fertilizers in sustainable and eco-friendly agricultural systems. Through their symbiotic relationships with plants, they recycle essential nutrients, restore soil health, and reduce environmental pollution [63]. For example, nitrogen-fixing endophytes such as *Azospirillum brasilense* and *Frankia* spp. reduce the need for synthetic nitrogen fertilizers by converting atmospheric or soil nitrogen into plant-available forms. This not only lowers production costs but also minimizes the negative environmental impacts associated with nitrogen fertilizer production and use [64]. Similarly, species of *Bacillus* and *Pseudomonas* improve phosphorus solubilization, making the nutrient more accessible to plants and reducing dependence on phosphorus-based fertilizers. Endophytes also play a vital role in supporting plant–fungal symbioses. For instance, *Pseudomonas* and *Bacillus* species enhance mycorrhizal development, thereby improving soil structure, expanding hyphal networks, and increasing nutrient uptake. Such mutualistic interactions strengthen plant resilience and promote soil fertility [65,66]. Additionally, certain endophytes, such as *Bacillus subtilis*, produce bioactive compounds that not only stimulate plant growth but also suppress plant pathogens, making them important biological control agents. Similarly, *Pseudomonas* species colonize plant roots, improve nutrient absorption, and protect crops from soil- and root-borne fungal infections, thereby reducing the need for synthetic fungicides. Actinorhizal symbioses with *Frankia* spp. further highlight the role of endophytes in natural nitrogen enrichment. Crop rotations involving plants that harbor these endophytes can reduce nitrogen stress and restore soil fertility. Beyond nitrogen and phosphorus management, diverse species such as *Actinomycetes, Azotobacter chroococcum, Bacillus amyloliquefaciens, Bacillus subtilis, Burkholderia phytofirmans, Enterobacter aerogenes, Streptomyces* *lydicus,* and *Herbaspirillum seropedicae* have shown great potential in promoting sustainable crop production [67]. By integrating these microbial partners into agricultural systems, farmers can reduce chemical inputs, minimize environmental pollution, and move toward a greener, more balanced form of agriculture. Thus, bacterial endophytes offer a powerful and natural alternative to conventional agrochemicals, ensuring resilience, productivity, and sustainability in future farming practices.

Bioprospecting from interactions between plants and endophytes: bioactive substances

The intricate association between plants and their endophytic bacteria has greatly advanced the field of bioprospecting. These interactions often lead to the production of novel bioactive compounds with significant pharmaceutical and industrial potential. The diversity of plant hosts and their endophytes represents a vast, largely untapped reservoir of chemical diversity, offering unique opportunities for the discovery of new metabolites. One of the major benefits of studying plant–endophyte interactions is the identification of secondary metabolites with valuable biological properties [68]. Because endophytes inhabit a specialized ecological niche within plants, they produce distinctive compounds that often display antioxidant, antibacterial, and anticancer activities. Such bioactive molecules are of great interest to the pharmaceutical industry, where they may serve as leads for the development of new drugs. For instance, antibacterial compounds from endophytes could help combat the growing challenge of antibiotic resistance, while anticancer metabolites may contribute to novel cancer therapies [69,70]. The relevance of endophyte-derived compounds extends well beyond pharmaceuticals. The cosmetics industry seeks antioxidant and anti-aging molecules for skincare formulations, while agriculture benefits from endophyte-produced biopesticides that provide eco-friendly and effective alternatives to chemical pesticides. A notable example is camptothecin, an important anticancer compound produced by endophytic *Pseudomonas* isolated from the *Camptotheca* tree. Such discoveries underscore the immense value of endophytes as natural bioprospecting agents [71]. Therefore, exploring plant–endophyte interactions opens promising avenues for the identification of bioactive compounds with diverse applications in health, agriculture, and industry. Harnessing this potential requires close collaboration between scientists and technological innovations, ensuring that the hidden chemical wealth of endophytes can be translated into sustainable solutions for global challenges.

Future prospects

Exploring the understudied domains of bacterial endophytes offers immense opportunities for discovery and innovation. These microorganisms can deepen our understanding of plant–microbe interactions and provide practical solutions to transform industries, promote sustainable agriculture, and address global environmental challenges. One particularly promising yet underexplored area is the role of endophytes in enhancing plant resilience to climate change. With increasing temperatures, droughts, and nutrient limitations, plants face growing stress. Endophytes that improve nutrient uptake, enhance drought tolerance, and strengthen host defences hold great potential for sustaining agricultural productivity under uncertain climatic conditions. Unravelling the molecular mechanisms behind endophyte-mediated stress tolerance could pave the way for climate-resilient farming systems.

Another exciting avenue is endophyte-mediated biotransformation, where pollutants and organic wastes are converted into valuable bio-products. This approach not only supports energy production but also contributes to ecosystem restoration and environmental sustainability. From an economic and ecological standpoint, endophytes represent a novel strategy for combating environmental degradation. The advancement of metagenomic tools has been a turning point, enabling researchers to study population dynamics in diverse, unexplored habitats and to identify novel genetic resources, bioactive compounds, and innovative ecosystem restoration strategies. Targeted gene studies may further reveal endophyte-derived metabolites with applications in agriculture, medicine, and industry. Endophytes also hold promise as biocontrol agents against invasive and resistant pests. Bioactive compounds produced by these microbes could serve as sustainable alternatives to synthetic pesticides, reducing dependence on harmful chemicals. Moreover, advances in genetic engineering provide opportunities to enhance specific endophytic functions, such as nutrient cycling, stress tolerance, and the degradation of complex substrates into useful compounds. These engineered endophytes could revolutionize agriculture, environmental remediation, industrial production, and medicine. Realizing this potential requires interdisciplinary collaboration, the use of advanced technologies, and a deeper understanding of plant–endophyte interactions. The future of endophyte research lies not only in curiosity-driven exploration but also in translating discoveries into practical solutions. By unlocking their untapped capabilities, bacterial endophytes could contribute significantly to building a more resilient, sustainable, and ecologically balanced future.

Conclusion

This study highlights the diverse roles of bacterial endophytes and their growing significance in sustainable industrial applications. They hold great promise for improving agriculture, driving innovation in biotechnology, supporting environmental remediation, and contributing to pest management. Their ability to enhance crop resistance, promote bioconversion, suppress pathogens, and degrade pollutants makes them valuable tools for multiple industries. In medicine and pharmacology, they represent a potential source of novel therapeutic compounds. However, integrating bacterial endophytes into commercial sectors is not without challenges. Regulatory restrictions, host compatibility issues, and the need for thorough safety and efficacy evaluations remain major hurdles. Overcoming these barriers will require close collaboration between researchers, industries, and regulatory bodies. Recognizing the potential of bacterial endophytes is essential to building a greener, more sustainable future. With continued scientific innovation, technological progress, and cooperative efforts, their untapped potential can be unlocked. The journey of bacterial endophytes is ongoing, and future studies will not only help address current challenges but also create lasting benefits for both humanity and the environment.

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Disclosure Statement

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