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REVIEW

Tiny partners in big roles: exploring Endophytes from medicinal and economically important plants for Sustainable Agriculture

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Endophytes are asymptomatic microbes that dwell in plant tissues and provide essential support systems for plant resilience, growth, and development. These microbes can be found in a large diversity of medicinal and economically important plants, with their own specialized metabolic capacity. Several recent studies highlight the role of endophytes in sustainable agriculture, where they represent a strategy for higher nutrient uptake, growth hormone production, environmental stress tolerance and pathogen resistance within plants. They also have potential use as new sources of bioactive compounds with applications in the pharmaceutical and agricultural industries. The present mini-review assembles the existing information available about the diversity of endophytes, their working mechanisms and potential applications in sustainable agriculture with special emphasis on medicinal plants, major crops and a few successful case studies from India.

Keywords : Endophytes, medicinal plants, sustainable agriculture, biocontrol, stress tolerance, plant-microbe interaction

INTRODUCTION

Endophytes are microbes such as bacteria, fungi and actinomycetes that exist within the internal tissue of plants without causing any obvious damage and they form a symbiotic relationship with the host plant to positively influence the way that plant grows, how it reacts to environmental stress and its ecological fitness (Negi *et al*. 2024). Recently, plant microbiome research has been gaining the interest of scientists and includes important information regarding plant health and productivity as it relates to microbial communities. The endophytes belong to another component of plant microbiomes because they are the partners that the plants rely on to survive through both biotic or abiotic stresses (Tariq *et al.*2025).

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The secondary metabolites that are produced by the plant influence how the endophyte colonises the plant and also allow for the opportunity to determine endophyte species that produce novel bioactive compounds (Upadhyay and Khandelwal, 2025).To date, a number of plant species, including medicinal plants, economically important crop plants, and trees, have been used as research material to study this type of symbiosis (Miguel *et al*. 2024). Endophytes are recognised as means of providing sustainability in agriculture through the promotion of nutrient cycling, pest resistance and stress tolerance. As indicated by both Tariq *et al*. (2025) and Watts *et al*. (2023), the eco-friendly benefits that endophytes provide create options that reduce the need for the use of chemicals. Endophytes can be described as microbial examples such as bacteria, fungi and Actinomycota, yet they occupy plant tissue internally and do not generally harm plants. Instead, endophytes are a symbiotic species that help to influence plant growth, health,stress tolerance and even ecological performance (Negi *et al.* 2024).Over the past several years, researchers have become very interested in the study of plant microbiomes and the concept of the microbial community in general as it relates to plant health, productivity, and sustainability. Endophytes constitute one element of this microbiome because they comprise partners that are not visible to the eye and help plant scope with biotic and abiotic stresses (Tariq *et al*. 2025). The metabolites of an endophytes organism are capable of influencing colonisation by other microbes and thus offer a form of screening of endophytes that have the potential to produce new kinds of bioactive metabolites (Upadhyay and Khandelwal, 2025). Many types of plants have been examined to study the symbiotic association between them and endophytes, including medicinal plants, economically valuable crop plants, and trees. Endophytic organisms can increase the sustainability of agricultural production through nutrient cycling, pest resistance, and stress tolerance. Eco-friendly systems like these provide options for the use of chemicals. (Tariq *et al.* 2025; Watts *et al.* 2023).The study of medicinal plants also involves the study of endophytes that influence the growth and endurance of these plants, which is critical in bioactive substance production. Economically important crops have obtained assistance through these little associates inimproving nutrient uptake and disease resistance, which are both critical in terms of sustainable agricultural methods (Khan *et al*., 2025; Gunjal, 2024). Endophytes in trees and perennials contribute biodiversity and balance to the ecosystem by creating stable and balanced ecosystems through the resilience of the ecosystem (Show *et al.* 2024). The semicrobes improve the way minerals such as phosphorus and potassium are absorbed byplants, because they dissolve the minerals, thus making them more available to plants (Gunjal, 2024). Endophytes are biocontrol agents that will produce compounds (called biochemicals/ modifiers, or metabolites) that protect plants from diseases and pathogens (Gunjal, 2024). The endophytes are able to support the abiotic stresses such as drought and extreme temperatures by controlling the phytohormones which are related to the stress inthe plants (Chhipa and Deshmukh, 2023). Despite the possibility of endophytes having a role in agricultural sustainability, there is a need to know the types of relationships between endophytes and their hosts. The research on utilising the endophyte-plant relationships is still continuing, to ensure their practical application in the agriculture and biotechnology sectors (Jaiswal *et al.* 2023).Endophytes are found in almost all plant types but there has not been much research onendophytes found in medicinal or agricultural plants. Endophytes from medicinal plants have special metabolic capabilities, yet little understanding exists about how they contribute to plant growth, stress resistance and yield. Research on crop endophytes is limited to a few types of culturable organisms, which has left a lot of unexplored potential. There is little in the way of comparative or mechanistic studies with field trials that can identify the best way to utilize these organisms as bioinoculants in sustainable agriculture and to reduce the useof chemicals. Bridging these gaps is essential for translating endophyte-based innovations into scalable agricultural solutions. In future agricultural systems, they are going to play a very large part in enhancing agricultural productivity without having to do any more harm to the environment (Fig. 1). It is through this research that we can look at ways of optimizing our ability to produce more food while also protecting our environment.

Diversity of endophytes in medicinal and economically important plants

Taxonomically, endophytes are diverse and range from bacterial genera such as *Bacillus,Pseudomonas* and *Enterobacter* to actinomycetes like *Streptomyces* and fungal genera such as *Trichoderma* and *Fusarium.* The different species mentioned colonise various plant tissues, including roots, stems, leaves and seeds of both medicinal and important economic crops (Ramamurthy *et al*. 2025). Endophytes found in medicinal or economically-important plants are made up of many types of different micro-organisms including bacteria, fungi and actinobacteria (Wang *et al*. 2023; Tariq *et al.* 2025). Bacteria have been reported assynthesising several bioactive compounds which may provide therapeutic benefit and have positive effects on plant growth through growth promotion and/ or increased resistance tostress (Prajapati *et al.* 2025; Sharma *et al.* 2023). The diversity of these endophytes (Table 1) is crucial for the development of novel pharmaceuticals and agricultural applications (Liu *et al.*2024; Prajapati *et al*. 2025).

Multiple factors influence the diversity of endophytes :

- o Plant genotype
- o Tissue specificity
- o Environmental conditions
- o Agricultural practices

Plants produce antimicrobial compounds that exert a selective pressure on endophytic organisms and therefore require both adaptive traits and metabolic flexibility (Semenzatoand Fani, 2024). The application of molecular biology techniques (e.g., Next-Generation Sequencing (NGS) and Metagenomics) over the last decade has significantly enhanced our understanding of endophytic diversity and the structure of these communities (Pednekar *etal.* 2025). The endophytes, linked to important economic plants, consist of numerous fungiand bacteria that significantly enhance the health, productivity, and robustness of plants, as indicated by Wang *et al*. (2023) and Tariq *et al.* (2025). The endophytes found inside the tissues of such plants can enhance the growth of the plants, increase their resistance to diseases and produce many useful secondary metabolites (Wang *et al.* 2023). This depicts the ecological functions, the variety of species and the potential uses of such microorganisms in the field of agriculture. Endophytic fungi are abundant in many types of plants, such as cocoa, soybeans,eucalyptus trees, etc., with a great diversity found in the leaves and stems of these trees (Souza, 2017 and Miguel, 2017). The diversity of endophytic fungi found in eucalyptus trees differs depending on how old the plant is or where on the leaves it is collected from, which shows that they are influenced by ecological factors (Miguel, 2017). In a study conducted on coffee plants and plants from the family Rubiaceae, there was a very high level of diversity in the fungal endophytes, with 659 different fungi being discovered. The study showcases therich diversity of the fungi that live in association with these types of plants in both natural andmanaged ecosystems (Castillo-González, 2022).Bacterial endophytes are found throughout plants and are vital in improving plant growth andtheir ability to cope with stress is accomplished through the production of phytohormones and resistance to environmental stresses (Mamarasulov and Davranov, 2024). Certain types of bacteria, specifically *Bacillus* and *Pseudomonas*, have been linked to greater plant resistance and growth, and therefore, the use of those types of bacteria in sustainable agriculture is very promising (Mamarasulov and Davranov, 2024).While the benefits of using endophytes have been known for a while, there still exist problems in understanding complex relationships between the two and actually implementing them into farming practices. More research will be needed before these can reach their full potential in helping to improve the health and production of crops.

Functional Mechanisms of Endophytes

There are several mechanisms through which endophytes improve plant nutrition such as-nitrogen fixation, phosphate solubilization and production of siderophores. These processes promote nutrient availability and uptake resulting enhanced plant growth and productivity (Tariq *et al*. 2025). Moreover, endophytes synthesise phytohormones, including auxins, gibberellins and cytokinins that control plant growth and development- as for e.g. bacterial endophytes were shown to produce indole-3-acetic acid (IAA), which results in rootelongation and branching (Tshikhudo *et al*. 2023) (Table 2).

Stress Tolerance and Climate Resilience

Endophytes impart tolerance to abiotic stresses (drought, salinity, and temperature extremes). They achieve this by increasing antioxidant enzyme activity, modulating genes responsive to stress and synthesize osmoprotectants. In the frame of climate change and soil degradation such mechanisms take on a key importance (Semenzato and Fani, 2024).

Biocontrol and Disease Suppression

Endophytes act as natural biocontrol agents by inhibiting plant pathogens through synthesis of antimicrobial substances,nutrient and space competition and induction of systemic resistance. Fungal endophytes are known to produce a variety of secondary metabolites that exertinhibition on pathogenic microorganisms (Nazir *et al*. 2024).

Secondary Metabolite Production

Bioactive compounds (e.g. alkaloids, terpenoids, phenolics and antibiotics produced by endophytes are a rich source of Alkaloids, Terpenoids, Phenolics and Antibiotics.These compounds are used in medical, agricultural, and biotech areas. Endophytes obtained from medicinal plants, including fungi and bacteria, play a pivotal role in mirroring or magnifying plant metabolic pathways with improved activity to produce novel compounds (Chandra *et al*. 2024).

Endophytes from medicinal plants: a unique resource

Endophytes with unique properties can be abundantly found in medicinal plants. Some of thesecondary metabolites produced by these plants can influence the endophyte community composition and function. Species of endophytes obtained from medicinal herbs have exhibited: enhancement in plant growth, improvement of plant tolerance to stress and they generate pharmacologically relevant molecules. Thus, conservation of medicinal plants is paramount not only for their direct use but also important for the associated microorganisms' diversity (Upadhyay and Khandelwal, 2025).

There are many studies on endophytic microbes found in medicinal plants (particularly bacteria and fungi) like *Ocimum sanctum, Cinnamomum camphora* and *Taxus wallichiana* in the Himalayan region. The microbes produce bioactive compounds possessing antimicrobial, anti-inflammatory and antiseptic properties (Singh *et al*. 2023). Plant-associated endophytic fungi from *Andrographis panticulata* and *Withania somnifera*give various applications like anticancer and antioxidative activities (Vallabhaneni *et al*.2023).

Medicinal plants' endophytes are a special and valuable bioresource for screening of bioactive compounds with important therapeutic potential. These have been observed to occupy plant tissues without causing any damage, and are gaining recognition for theproduction of secondary metabolites that can exceed those of their host plants (Semenzato and Fani, 2024). Endophytes from the roots, stems and leaves of medicinal plants display a wide variety of species like *Aspergillus, Fusarium*, and *Bacillus* (Mani *et al.* 2025; Rana *et al.* 2020). A research effort identified 126 endophytes and provided a catalogue of 71 novel metabolite features and a high number of both antimicrobial and antioxidant substances (Mani *et al*. 2025). Bioprospecting of endophytes generates valuable sources of natural products to either manufacture or produce pharmaceutical, agricultural and industrial products (Rana *et al.* 2020; Kaur and Kaur, 2020). Furthermore, endophytes produce many types of bioactive compounds, including alkaloidsand flavonoids, that can be used to treat different types of disease as well as promote plantgrowth (Choudhury *et al.* 2023; Wang *et al.* 2023). Endophytes are well known for their antitumor and antimicrobial effects, thus they are ideal candidates for drug development.Their metabolites offer less toxic alternatives to traditional drug therapies, enabling the development of therapeutics that require less toxic drug options (Kaur and Kaur, 2020).The potential uses for endophytes are numerous; however, the challenges of isolation and characterization of endophytes may impair the ability to realize their full potential. Continued research will be needed to fully exploit the potential therpeutic and agricultural advantages ofthe endophytes.

India-specific case studies

Several studies from India have shown research on endophytes specifically from India (Table 3).

Some of these are discussed below:

Endophytes from Azadirachta indica (Neem)

In India, Neem is an established medicinal plant known for its antimicrobial and insecticidal properties. The usage of endophytes from Neem, has been studied for their:

- Antifungal properties against plant pathogens
- Development of bioactive metabolites
- Possibility of being used as biopesticides

Research indicates that endophytes associated with Neem can assist with natural pest resistance and could be used in sustainable agriculture (Verma *et al.* 2007; Verma *et al.*2011; Purohit *et al.* 2025; Chutulo and Chalannavar, 2018). Studies have found endophytes isolated from Neem to have antifungal properties against different types of plant pathogens.One example includes: Endophyte *Aspergillus* sp. isolated from Neem, exhibited antifungal effects towards several different types of phytopathogenic fungi, *Fusarium graminearum* (Jain and Sharma, 2014). Through testing, endophyte fungi and bacteria were isolated fromthe leaves of Neem that developed antifungal properties toward *Candida albicans* andseveral different *Aspergillus* species (Kadam and Kanase, 2023).The presence of neem endophytes is characterised by abundant sources of bioactive biosynthesis, including azadirachtin, nimbidin, and nimbolide among others, which are all proven to possess antimicrobial, antifungal, and antitumoral properties (Ricci *et al.* 2022). Intotal, there have been over thirty types of biosynthesis due to neem's association with endophytes, all contributing to the different biological activities of endophytes (Kharwar, 2020).

The efficacy of neem in pest control is well established and the metabolites produced by endophytes serve to improve the insecticidal properties of the plant through enhancednatural insect resistance (Sindhu and Chauhan, 2025; Kharwar *et al.*, 2020). Endophytes have also been used to explore whether they can produce neem "mimetic" compounds which may then be utilised to create biopesticides (Kharwar *et al.,* 2020). *Azadirachta indica*provides support for environmentally sustainable practices of crop protection and improved pest management through its association with endophytes that have antifungal properties against plant pathogens (Kumar *et al.* 2025).

Endophytes from Withania somnifera (Ashwagandha)

Medicinal plants have been known for their important uses in both Eastern and Western medicine. Ashwagandha is one type of medicinal plant that is used in traditional Indian medicine as an adaptogen, as it helps to reduce stress. After isolating endophytes from this plant, it has been shown that they produce more with anolides, promote plant growth, andincrease the ability to tolerate environmental stress. Due to the number of endophytes isolated from Ashwagandha, it can be concluded that these microbes can improve yields andquality of the phytochemicals (e.g., methylation of polysaccharides, terpenoids, alkaloids) produced by *W. somnifera* (Kumar *et al*. 2012; Mishra *et al.* 2013; Singh *et al.* 2017). Endophytes include both fungal and bacterial species found in W. somnifera and have beenshown to be important in increasing the size and secondary metabolite production of theplant, as measured by the amount of withanolides produced. The endophyte-plantrelationship is complex and can vary greatly depending on environmental factors and whereon the plant the endophyte is found (Patel *et al.* 2024). There are 131 different species of endophytic fungi isolated from the various parts of *W. somnifera* and the seasonal colonization rate of endophytes can vary; 42.67% of the fungi were isolated during the winter months, 7.33% during the summer months, and 37.33% during the rainy season. Thepredominant genera of endophytic fungi in *W. somnifera* were *Alternaria, Fusarium* and *Chaetomium*, with specific species such as *Fusarium moniliformae* and *Chaetomium globosum* being dominant in the winter (Patel *et al.* 2024). The enzymatic activities exhibited by bacterial endophytes isolated from *W. somnifera,* including amylase, protease, and esterase, have significant implications for their potential biotechnological applications. Co-inoculation of fungal endophytes, primarily *Trichoderma viride*, with *W. somnifera* significantly enhanced the growth parameters of the plant as well as the amount of with anolides present. The co-inoculation also increased the expression ofgenes associated with with anolide biosynthesis and ultimately enhanced the plants potential to provide medicinal benefits (Kushwaha *et al.*2019).

Research indicates that endophytes modulate the localization and abundance of withanolide biosynthesis sites in *W. somnifera*. Some endophytes can induce the production of thenormally absent phytoestrogen withaferin A from the root tissue of *W. somnifera* by up-regulating certain genes involved in the biosynthesis of with aferin A (Pandey *et al.* 2018).

The interaction of endophytes and the host plant continues to evolve, and further research will be necessary to identify how these interactions can be optimally utilized to provide greater health benefit to consumers.

Endophytes from Ocimum sanctum (Tulsi)

Tulsi, commonly referred to as Holy Basil, is well known for having properties that make it beneficial in both traditional medicine and antimicrobial use. The endophytic fungi and bacteria obtained from Tulsi (*Ocimum sanctum*) have been shown to provide antimicrobial activity, support plant growth and support plants under environmental stress.These endophytes can be used as bioinoculants within agricultural systems, according to research (Kumar *et a*l. 2011; Singh *et al.* 2019; Verma *et al.,* 2016).The fungi that exist within Tulsi demonstrate a diverse population of endophytes that contribute to the Medicinal Properties of Tulsi. There are a number of Fungal Endophytes that have been identified within Tibasil, as potential Biocontrol Agents, as well as Sources of Bioactive Compounds. Namdev *et al.* (2024) isolated 5 different endophytic fungal strains from Tibasil, which represent a diverse mycobiota on Tulsi plants. In another study, Chowdhary and Kaushik (2015) identified a total of 90 fungal isolates from 17 genera, with significant differences in endophyte diversity based on region as well as the specific plant tissue from which they were isolated. The endophytes associated with Tulsi (*Ocimum sanctum)* have shown noteworthy antimicrobial, anticancer, and anti-virulence properties and represent an important source ofnovel bioactive compounds (Shinde *et al.* 2025). Specific endophytes have demonstrated astrong biocontrol potential against various plant pathogens, with some having a high efficacy against the plant pathogen Sclerotinia sclerotiorum (Chowdhary and Kaushik 2015). Additionally, endophytes have produced cellulases and pectinases, which may have industrial applications (Shekhawat and Shah 2013). Although the literature has addressed the enhancement of the therapeutic properties of *Ocimum sanctum* by endophytes, there should be an awareness of the ecological balance and risks involved with introducing endophyte species into a new environment. Rice and wheat contain many fungi and bacteria;endophytes play a critical role in assisting plants to grow better, healthier and with stand avariety of stressors. The endophytes in staple crops do this through multiple means. Among the staple crops, wheat has the most diversity of endophytic fungi (N=157), while rice has avariety of endophytes that also benefit rice (Fan and Shi, 2024; Yousefi and Hasanzadeh, 2019).Endophytes are known for their ability to improve plant growth and to provide pest andpathogen suppression and should be considered in sustainable agricultural systems (Yousefi and Hasanzadeh, 2019). They promote plant growth through hormone stimulation, nitrogen fixation, and by producing siderophores, which increase the availability of nutrients (Maji *et al*. 2022). They also provide systemic resistance to pests and environmental stressors, increasing crop resilience (Deka *et al.* 2022). Some endophytic fungi, such as Beauveria and Metarhizium, can also contribute to the management of pest populations ingrains while promoting plant growth (Chandraleka *et al.* 2024). Although the contributions of endophytes have been clearly established, further investigationis necessary to determine the best approach for both understanding their mechanisms of action and their utility in agricultural systems. Additional research is critical to utilize the benefits they may provide.

Himalayan Medicinal Plants

Biodiversity is abundant in the Himalayas, including the North-eastern Region of India where large numbers of species of various medicinal plants can be found. Many of these species also contain endophytes and endophyte-associated metabolites that have potential for use as biotechnological innovations, such as climate-resilient agricultural systems (Sharma *et al.,*2021; Devi *et al*. 2021). Additionally, some endophytes demonstrate tolerance to extreme environmental conditions as well as production of unique chemical compounds (Jain *et al.*2021), thus contributing to the resilience of plants by enhancing their ability to adapt toadverse conditions (Jain *et al.* 2021). In the Sikkim Himalaya region, *Penicillium citrinum* has been isolated from *Swertia chirayita* and was shown to inhibit the in vitro growth of phytopathogenic fungi *(Fusarium solani, Colletotrichum gloeosporioides, Alternaria alternata, Pestalotiopsis theae and Sclerotinia sclerotiorum.)* by producing antimicrobial metabolites such as protease, amylase, cellulose, chitinase, as well as, indoleacetic acid and siderophores. Also, this endophyte has exhibited significant antifungal activity against Phytopathogenic fungi such as *Fusarium solani, Colletotrichum gloeosporioides, Alternaria alternata, Pestalotiopsis theae*, *Sclerotinia sclerotiorum* and many others (Sharma *et al.* 2021).

Endophytes are known to produce a vast array of bioactive compounds with documented antibiotic and secondary metabolite potential for pharmaceutical use (Nisa and Kamili, 2019). They have long been documented for their therapeutic value, and the most notable ones such as *Tolypocladium niveum* or *Cylindrocarpon* lucidum has been reported to possess anti-inflammatory, antimycotic and pain-relieving properties (Singh *et al*. 2023).Various diverse groups of endophytic fungi including *Aspergillus* spp. and *Trichoderma spp.*have been explored for their potential roles in agriculture/medicine to enhance plant growthand provide biocontrol of pest problems. Endophytes are being evaluated for their potential application in sustainable agriculture to enhance climate resilience (Rana *et al.* 2020). Despite the great potential of Himalayan endophytes, many factors can pose a threat to these valuable resources, including habitat destruction and unsustainable harvesting.

Therefore, conservation of these natural resources is vital for continued harvesting of these important plants and their endophytes.

Role of endophytes in sustainable agriculture

Endophytes contribute to sustainable agriculture in multiple ways, as shown in Table 4:

Biofertilizers

Endophytes are good microorganisms that support plants by supplying them with growthre gulators, fertilizers, and biopesticides and helping the plants develop and be successful (Rai, 2024). They also assist with recycling nutrients and making them available, which candecrease the amount of chemical fertilizers that a plant needs to grow (Bhattacharya and Jha, 2025; Singh *et al.* 2023; Das *et al.* 2025; Santoyo *et al*. 2016).

Biopesticides

Endophytes are also able to create chemical compounds called secondary metabolites thatcan kill or stop the growth of many different types of living things that are harmful to plantsand reduce the need for chemical insecticides and fungicides (Sharma *et al.* 2022; Xu *et al.*2021). The endophytes produce these compounds and also stimulate the plant to make it sown defense compounds, making endophytes a natural alternative to synthetic pesticides (Rabbee *et al.* 2024).

Soil Health Improvement

Endophytes play an important role in enhancing soil structure, increasing microbial diversity,and improving nutrient cycling, all of which contribute to sustainable agricultural practices (Santoyo *et al.* 2016; Sharma *et al.* 2022).

Climate Resilience

The use of endophytes in agriculture supports the goals of sustainable development and environmental stewardship (Das *et al.* 2025; Rodriguez et al. 2009; Lata *et al*. 2018; Das e*tal*. 2025).

Employing endophytes might result in sustainable agriculture and alleviate many other problems related to global food security (Rai, 2024).

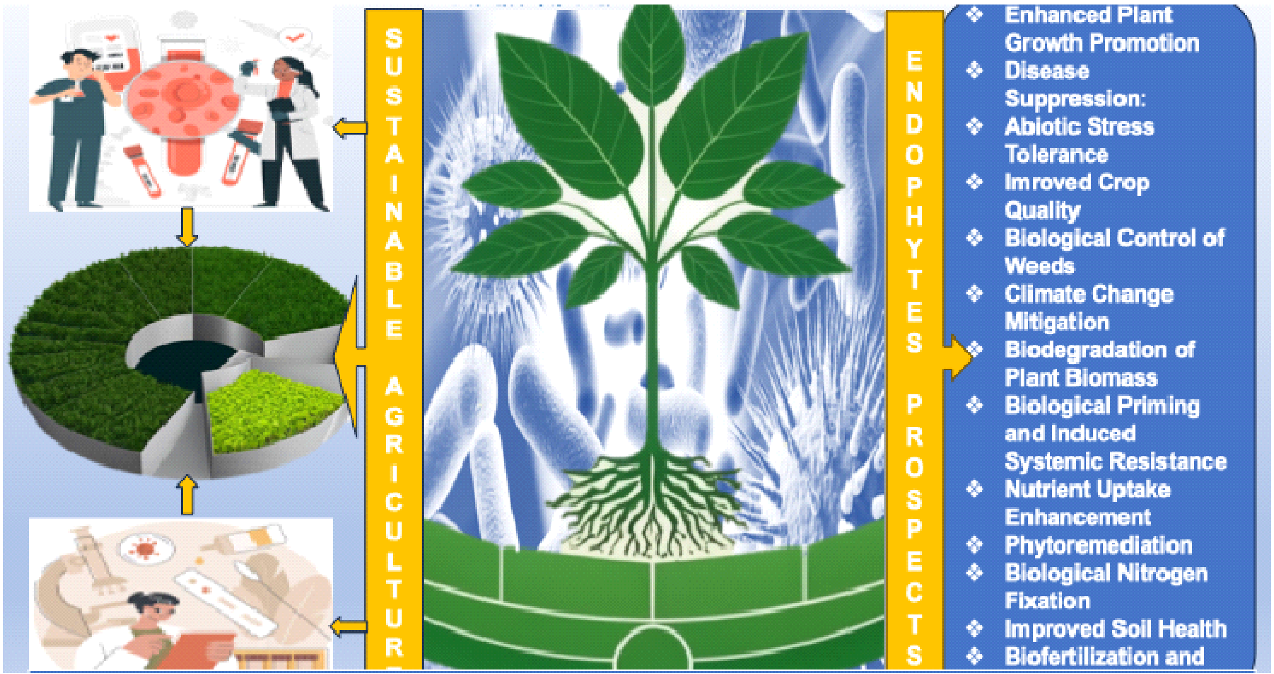

Fig 1: Conceptual illustration of the role of endophytes in sustainable agriculture, highlighting their functions in promoting plant growth, enhancing stress tolerance, improving nutrient uptake, and supporting eco-friendly crop production

Challenges and limitations

While they hold great promise, there are multiple barriers to the practical use of endophytes on a large scale:

- ❑ Drastic variations in field performance
- ❑ Host specificity
- ❑ Large gap because we do not yet understand the microbial interactions
- ❑ Formulation and commercialization hurdles

The solution of these challenges needs cross disciplinary research and development.

Future prospects

Future research should focus on:

Data from multi-omics approaches (genomics, proteomics, metabolomics)

- ❑ Engineering of microbiome
- ❑ Bioformulations Stabilization
- ❑ Field validation studies

These areas of advance will allow endophytes to be effectively employed in sustainable farming.

CONCLUSION

Known as tiny partners, endophytes work in a surprisingly important and complex mannerto contribute to plant growth and enable sustainable agriculture. These microbes, residing within their host plant tissues, are highly abundant in medicinal and economically important plants, providing valuable reservoirs of beneficial microbial resources. For these reasons,their versatile and multifunctional properties not only promote plant growth, improve nutritional uptake, resistance to biotic and abiotic stresses but also coordinate the biosynthesis of natural products key for human health and ecological balance. Therefore,they are indispensable for developing of innovative and sustainable agri-food systems in thefuture. Exploit their tremendous potential through deployment of modern biotechnological tools and applications in the fields will play crucial role in development of sustainable andresilient agriculture systems to cater to the challenges of a changing global environment.

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Table 1 : Diversity of Endophytes in Medicinal and Economically Important Plants

Category	Description	RepresentativeGenera	KeyFeatures
Bacterial endophytes	Colonize internal plant tissues	*Bacillus, Pseudomonas, Enterobacter*	Nutrient cycling, Plant growth promotion
Fungal endophytes	Symbiotic fungi in plant tissues	*Trichoderma, Fusarium*	Secondary metabolite production
Actinomycetes	Filamentous bacteria	*Streptomyces*	Antibiotic production
Tissue specificity	Root, stem, leaf, seed colonization	*Bacillus, Trichoderma, Streptomyces* (depending on tissue)	Tissue-dependent diversity
Influencing factors	Genotype, environment, agronomy	*Bacillus,Pseudomonas, Trichoderma, Streptomyces*	Shape microbial composition
Medicinal plant association	Chemically rich host environment	*Penicillium,Fusarium,Bacillus*	Drives metabolic adaptation

Source of data: Ramamurthy*etal.*(2025);Semenzato and Fani(2024);Pednekar*etal.*(2025).

Table 2 : Functional Mechanisms of Endophytes

Functional Role	Mechanism	Biological Activity	Agricultural Outcome
Nutrient acquisition	Nitrogen fixation	Converts atmospheric N	Enhanced growth
	Phosphate solubilization	Mobilizes insoluble P	Improved uptake
	Siderophore production	Iron chelation	Micronutrient availability
Growth promotion	Phytohormone synthesis	IAA,GA, cytokinins	Root/shoot development
Stress tolerance	Antioxidant enzymes	ROS detoxification	Stress resistance
	Gene regulation	Stress-response activation	Climate adaptation
	Osmoprotectants	Solute accumulation	Drought/salinity tolerance
Bio-control	Antimicrobial compounds	Pathogen inhibition	Disease suppression
	Competition	Resource exclusion	Reduced infection
	Induced resistance	Systemic signaling	Enhanced immunity
Secondary metabolism	Bioactive compounds	Alkaloids,terpenoids	Pharma/agri applications

Table 3 : India-Specific Case Studies

Plant Species	Common Name	Endophytic Benefits	Applications
Azadirachta indica	Neem	Antifungal activity,metabolite production	Biopesticides,cropprotection
Withania somnifera	Ashwagandha	Withanolide enhancement, stresstolerance	Medicinal yield improvement
Ocimum sanctum	Tulsi	Antimicrobia lactivity, growthpromotion	Bioinoculants
Rice (*Oryza sativa*)	Rice	Nutrient uptake, drought tolerance	Crop productivity
Wheat (*Triticum aestivum*)	Wheat	Disease resistance, growth promotion	Sustainable farming
Himalayan Medicinal Plants	—	Cold tolerance,unique metabolites	Climate-resilient agriculture

Table 4: Role of Endophytes in Sustainable Agriculture

Application Area	Mechanism	Benefit
Bio fertilizers	Nutrient cycling, nitrogen fixation	Reduced chemical fertilizeruse
Bio pesticides	Antimicrobial compound production	Reduced pesticide dependency
Soil Health	Microbial diversity enhancement	Improved soil fertility
Climate Resilience	Stress tolerance mechanisms	Stable crop yield under stress
Environmental Sustainability	Reduced agro chemical input	Eco -friendly agriculture

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DECLARATION

Conflict of Interest. The author declares no conflict of interest.

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