**REVIEW ON ENDOPHYTES IN ABIOTIC AND BIOTIC STRESS ALLEVIATION**

**Abstract:**

Endophytes, typically fungal or bacterial microbes residing within plant tissues without causing disease, hold promise for revolutionizing crop production. They enhance host plant survival against biotic and abiotic challenges by directly improving nutrient uptake and modulating plant hormones. Indirectly, they contribute to plant health by deterring pathogens with antibiotics and enzymes, reducing nutrient availability for pathogens and activating defense mechanisms. This review delves into their diverse mechanisms, offering sustainable alternatives to chemical interventions. Understanding their role in stress alleviation is crucial for advancing agricultural practices and ensuring global food security.

Keywords: Endophytes, Abiotic and Biotic stress, Plant growth

**Introduction**

**Global Food Security Challenge**

Agricultural practices face an increasing demand to generate higher yields to feed the growing global population, which is expected to reach 9.7 billion by 2050. The year 2009 witnessed 8.9% of the world's population suffering from hunger (Anon, 2009), highlighting the urgent need for reliable and sustainable food production. However, abiotic and biotic stresses, such as saline stress, flooding, drought, soil fertility issues, heat, heavy metals and phytopathogens, create unpredictable challenges for agricultural yields. threat of climate change further amplifies the frequency, intensity and geographical spread of these stressors. For example, Otlewska *et al*. (2020) reported that currently approximately 20% of the total cultivable land faces saline stress globally and this is projected to increase to 30% by 2050.

**Endophytes: A Solution to Food Security.**

Recent research on endophytes has gained attention for their potential to revolutionize crop production. De Bary (1866) defined endophytes as "Any organism growing within plant tissues," distinguishing them from epiphytes, which reside on plant surfaces. Carroll *et al*. (1986) further refined the definition, describing endophytes as "Organisms inhabiting aerial plant parts and living tissues without causing visible infection or diseases," emphasizing mutualistic relationships while excluding pathogenic and mycorrhizal fungi. Petrini *et al*. (1991) expanded on this definition, characterizing endophytes as "Organisms colonizing plant tissues during part of their lifecycle without causing symptomatic infections.

**Types of Endophytes**

Hardoim *et al*. (2008) classified endophytes into three categories: Passenger endophytes, which enter the plant by chance and become endophytic, typically restricted to the root cortex tissue; Opportunistic endophytes, which occasionally enter for their own benefits and exhibit specific root colonization characteristics, confined to particular plant tissues; and Competent endophytes, which possess all the properties of opportunistic endophytes and additionally, are well adapted to the plant environment. Competent endophytes are capable of invading specific plant tissues, such as vascular tissue and spreading throughout the plant.

**Endophytes Diversity**

Endophytes, which involve fungi, bacteria and actinomycetes, contribute significantly to plant health and adaptation across diverse ecosystems. Among endophytic fungi, three major taxonomic groups are prominent: Ascomycota, Zygomycota and Basidiomycota. Leuchtman and Clay (1988) observed endosymbiotic fungal species such as *Balansia*, *Epichloe* and*Neotyphodium* in desert plants, protecting against desiccation within the moist internal tissue of the host. Endophytic bacteria, including genera like *Bacillus*, *Agrobacterium*, *Brevibacterium*and *Pseudomonas* (Sun *et al*., 2013) are well-documented for their beneficial roles in plant growth and stress tolerance. Liu *et al*. revealed a diverse array of endophytes inhabiting wild rice, with Proteobacteria, Bacteroidetes and Firmicutes among the dominant phyla. Additionally, endophytic actinomycetes, commonly isolated from various plants, exhibit a particular prevalence in mangroves and medicinal plants of tropical rainforests. *Streptomyces* and *Micromonospora* are among the dominant genera within this group (Qin *et al*., 2010).

**Endophyte-Plant Relationship, Colonization and Transmission**

Schenk *et al*. (2012) described the plant-endophyte relationship as a mutualistic one, characterized by symbiosis in which endophytes reside within plants without causing harm. In return, endophytes provide several benefits to their host plants, including improved nutrient uptake, enhanced stress resistance and protection against diseases and pests.

Pinski *et al*. (2019) explained the colonization and distribution patterns of endophytes, highlighting key stages in their interaction with plant hosts. The process begins with the chemotactic movement of bacteria towards plant roots in response to exudates released by the plant, facilitating their detection and motility towards roots. Subsequently, endophytic bacteria adhere to the root surface, a critical step in invading plant tissues. To establish successful interactions, endophytic bacteria produce various molecules related to chemotaxis, motility, adhesion and biofilm formation, along with cell wall-degrading enzymes. This aids in biofilm formation and penetration of the outer root tissues, enabling invasion of the inner plant tissues. Ultimately, bacteria enter plants through roots and spread to other parts of the plant, contributing to the establishment of endophytic colonization and distribution within the host.

Marzouk *et al*. (2022) reviewed and summarized the transmission of endophytes, highlighting two main pathways: vertical and horizontal transmission. Vertical transmission occurs through seeds, allowing endophytes to pass from one generation to another. On the other hand, horizontal transmission involves the entry of fungal and bacterial endophytes into plants through various routes, such as open wound sites, breaks in root tissues, or natural openings like stomata. These pathways facilitate the colonization of plants by endophytes and play a crucial role in their distribution and establishment within host organisms.

**Benefits of Endophytes in Crop Stress Alleviation**

Chaturvedi *et al*. (2016) identified two main stress alleviation mechanisms of endophytic bacteria. Firstly, they directly benefit plants by enhancing nutrient uptake and promoting growth through hormone modulation. Secondly, they indirectlysupport plant health by deterring pathogens with antibiotics and lytic enzymes, reducing nutrient availability for pathogens and activating plant defense mechanisms.

**1.Enhancing nutrient uptake**

Endophytes play a vital role in enhancing nutrient uptake for plants. They achieve this by facilitating nitrogen fixation, which enhances nitrogen availability for host plants through nitrogenase activity. Nitrogen-fixing bacteria such as *Azoarcus* sp. BH72, *Azospirillumbrasilense*, *Burkholderia* spp., *Gluconacetobacterdiazotrophicus* and*Herbaspirillumseropedicae* promote plant biomass by fixing nitrogen (Bhattacharjee*et al*., 2008). Additionally, endophytes contribute to phosphorus availability for plants by making insoluble phosphates soluble through processes like acidification, chelation, ion exchange and organic acid production. Studies have shown that 59–100% of endophytic populations from cactus, strawberry, sunflower, soybean and other legumes are mineral phosphate solubilizers (Palaniappan *et al*., 2010). Moreover, endophytes produce iron-chelating agents called siderophores, which help plants access insoluble iron. Siderophores enable plants to acquire iron, benefiting plant growth under iron limitation and contribute to discouraging phytopathogen growth by possibly depleting available iron (Ahmad *et al*., 2008).

**2**. **Improving plant growth through hormone modulation**

Endophytes play a crucial role in improving plant growth through hormone modulation, particularly by modulating levels of the plant hormone indole-3-acetic acid (IAA). IAA has been shown to enhance root development, increase root biomass and stimulate lateral root formation in host plants (Glick, 2012). However, the impact of IAA production varies: moderate levels promote growth, while excessive production can lead to stunted growth and stress responses in plants (Malik & Sindhu, 2011). To maintain a balance in IAA levels within the plant, some endophytic bacteria possess the ability to degrade IAA (Leveau & Lindow, 2005), ensuring optimal growth and development of the host plant.

Endophytes play a significant role in controlling ethylene levels in plants. Ethylene regulates various physiological processes such as root initiation, leaf senescence, root nodulation, abscission, cell elongation, fruit ripening and auxin transport. Increased ethylene production in response to biotic and abiotic stresses can inhibit root elongation, lateral root development and root hair formation. To mitigate these effects, endophytes produce the enzyme ACC deaminase, which breaks down ACC, a precursor of plant ethylene (Sun *et al*., 2009). By regulating ethylene levels, endophytes help to maintain optimal plant growth and development, particularly under stress conditions.

**3**. **Activating plant defense mechanisms**

Endophytes indirectly promote plant growth by suppressing phytopathogens through competition for niche and nutrition. By occupying invasion sites of pathogens in plants and utilizing nutrients, endophytes reduce pathogen invasion (Rodriguez *et al*., 2009).Furthermore, endophytes trigger plant disease resistance through two main mechanisms: Induced Systematic Resistance (ISR) and Systemic Acquired Resistance (SAR). ISR, dependent on Jasmonic Acid (JA) and Ethylene (ET) signaling, primarily controls resistance to necrotrophic pathogens, while SAR, dependent on Salicylic Acid (SA) signaling, confers resistance to biotrophic pathogens.

**4**. **Deterring pathogens with antibiotics and lytic enzymes.**

Endophytes are prolific producers of secondary metabolites, many of which exhibit potent antibacterial and antifungal properties (Gunatilaka, 2006). Compounds such as terpenoids, flavonoids, peptides and alkaloids have been extensively studied for their ability to inhibit pathogens. For instance, altersetin, an alkaloid produced by the endophyte *Alternaria* spp., has shown strong potential in inhibiting numerous pathogenic gram-positive bacteria (Hellwig *et al*., 2002).

Additionally, endophytes are known to produce a diverse array of enzymes, including chitinases, cellulases, β-1,3-glucanases, pectinases, glucanases and proteases (Gao *et al*., 2010). These enzymes play crucial roles in degrading the cell wall of pathogens, inhibiting spore germination and suppressing phytopathogens. Through the production of both secondary metabolites and enzymes, endophytes contribute significantly to the defense mechanisms of their host plants, ultimately enhancing plant health and resilience against microbial pathogens.

**Endophyte-Mediated Mechanisms for Specific Stress Alleviation**

**1. Drought Stress**

Drought, characterized by a decrease in available water in the plant rhizosphere, can significantly impact various physiological processes in plants, including chlorophyll fluorescence, chlorophyll content, photosynthetic rate, stomatal conductance, transpiration rate and phytohormonal content (Bhatt and Rao, 2005; Verslues *et al*., 2006; [Mathobo *et al*., 2017](https://www.sciencedirect.com/science/article/pii/S0176161720300535#bib0535)). Yandigeri *et al*. (2012) investigated the effects of seed-coated *Streptomyces* spp. Endophytes on wheat under drought stress and observed increased growth parameters (biomass, root and shoot length) and yield, attributed to enhanced production of indole-3-acetic acid (IAA).Similarly, Halo *et al*. (2020) studied the impact of soil incorporation of the fungal endophyte *Talaromycesomanensis* on tomato plants under drought conditions. They observed increased biomass, shoot and root length, yield parameters and reduced pollen sterility. These effects were associated with enhanced levels of photosynthetic pigments and ascorbic acid, elevated levels of gibberellic acid (GA) and improved anatomical parameters of stems. These findings highlight the potential of endophytic microorganisms to mitigate the adverse effects of drought stress on plant growth and productivity.

**2. Salinity stress**

Salinitydisrupts cellular ionic balance, leading to increased concentrations of Na+, Cl−, Mg2+, K+ and Ca2+ ions inside cells (Suzuki *et al*., 2016). This imbalance triggers oxidative stress, impacting processes such as photosynthesis, lipid bilayer functioning and cellular metabolism, ultimately resulting in reduced plant growth and crop yield (Chen *et al*., 2009).Shahzad *et al*. (2017) investigated the effects of soil drenching with the *Bacillusamyloliquefaciens* endophyte on rice under salinity stress. They observed increased growth potential in rice, attributed to the regulation of abscisic and salicylic acids, alongside enhanced amino acid production.Similarly, Abdallah *et al*. (2018) examined the impact of seed-coated *Bacillussubtilis* endophytes on chickpea plants under salt stress. They noted increased biomass and chlorophyll pigments, driven by enhanced uptake of N, K and Mg, along with increased production of enzymatic and non-enzymatic antioxidants and reduced levels of malondialdehyde (MDA), proline and hydrogen peroxide (H2O2).

**3. Heat stress**

Heat stress exerts significant effects on the morphological and physiological functions of plants, including alterations in plasma membrane permeability, water content regulation (via transpiration) and impaired photosynthetic activity. Heat stress also disrupts enzyme functioning, cell division and leads to increased production of reactive oxygen species (ROS), ultimately resulting in stunted plant growth (Kim *et al*., 2012).Waqas *et al*. (2015) investigated the impact of soil incorporation of the *Paecilomycesformosus* endophyte on rice plants under prolonged heat stress conditions. They observed increased biomass and chlorophyll content, attributed to elevated protein levels and modulation of abscisic acid and jasmonic acid hormones.Similarly, Ali *et al*. (2018) evaluated the effect of endophytic priming with *Thermomyces* spp. on cucumber plants subjected to heat stress. They observed increased root length and enhanced photosynthesis processes due to accumulation of metabolites (such as saponin, flavonoid, protein, carbohydrate) and production of antioxidants (SOD, CAT, POX) enzymes.Furthermore, Mukhtar *et al*. (2023) investigated the impact of seed priming with the *Bacillussafensis* endophyte on two tomato varieties under heat stress conditions. They observed increased growth potential characterized by enhanced antioxidant production, relative water content and reduced membrane electrolyte leakage.

**4. Heavy metal stress**

Anthropogenic practices such as metals mining, fossil fuel combustion, fertilizer and pesticide use and sewage sludge dispersal lead to soil contamination with heavy metals (Ullah et al., 2015). Elevated levels of heavy metals in soil adversely affect various physiological and biochemical activities in plants, ultimately leading to stunted growth and reduced yields (Rajkumar *et al*., 2013).Ashraf *et al*. (2018) evaluated the impact of an endophyte consortium on tannery effluent remediation in para grass constructed wetlands. They observed increased para grass biomass, reduction in pollutants such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD) and improved tannery effluent quality. Moreover, the enhanced phytoremediation capacity led to a reduction in heavy metals in the effluent.Similarly, Bilal *et al*. (2020) reported that combined soil incorporation of *Paecilomyces* spp. and *Penicillium* spp. endophytes on soybean plants under combined abiotic stress enhanced various growth parameters such as biomass, photosynthesis rate and pigment content. This enhancement was attributed to increased uptake of essential nutrients like Ca,K and Mg, stimulation of antioxidant production and regulation of endogenous hormones such as abscisic acid and jasmonic acid.

**5. Biotic stress**

Infestations of insect herbivores and pathogens are a significant threat to crop production. Plants employ various defense mechanisms to combat these threats, including the biosynthesis of jasmonic acid (JA) in response to insect chewing or mechanical wounding and salicylic acid (SA) in response to sucking insect attack (Vos *et al*., 2013; Singh *et al*., 2018). Early defense mechanisms post-pathogen attack includes the production of reactive oxygen species (ROS), activity of defense-related enzymes, cell wall reinforcement and accumulation of phenolics and lignin (Llorens *et al*., 2017). Mishra *et al*. (2018) investigated the effects of *Bacillusamyloliquefaciens* and *Pseudomonasfluorescens* endophytes applied via seed coating and foliar spray on ashwagandha against Alternaria alternata pathogen. The combined application of endophytes resulted in enhanced shoot length and fresh weight, reduced plant mortality, improved physiological performance, increased antioxidant production along with reduced ROS levels (H2O2, O2-) and programmed cell death. Similarly, Daroodi *et al*. (2021) explored the impact of *Acrophialophorajodhpurensis* endophyte soil incorporation on tomato against *Alternariaalternata* pathogen. They observed a reduced disease index of the pathogen and enhanced plant growth, attributed to antioxidant enzyme production, increased phenol and lignin content, improved relative water content and membrane stability index, leading to a reduction in cell death. Regarding infestations by insect herbivores, Chen *et al*. (2022) studied the impact of the *Piriformosporaindica* endophyte on rice under rice leaf folder infestation. They noted increased root and shoot weight, along with reduced larvae relative growth rate and metamorphosis, attributed to reduced lipid peroxidation, increased superoxide dismutase (SOD) enzyme activity and balanced JA levels.

**Conclusions and Future Prospectives**

In conclusion, the utilization of endophytes presents a promising approach to enhance both abiotic and biotic stress resistance in plants. Endophytes mitigate various stresses through mechanisms such as photosynthetic responses, activation of antioxidant enzymes, modulation of hormones, regulation of amino acids and deposition of lignin. Furthermore, they promote the development of robust root systems, leading to increased nutrient uptake and improved nutrient availability through the production of organic acids. Endophytes also induce systemic resistance in plants, elevating their ability to withstand a wide range of stresses. By Utilizing the benefits of endophytes, agricultural practices can achieve higher crop yields, reduce reliance on pesticides and improve water management, thereby promoting sustainable agriculture.

Future efforts in endophyte research should prioritize the development of strains that effectively address both abiotic and biotic stresses while possessing plant growth-promoting traits. Additionally, further exploration into the interactions between endophyte inoculation and indigenous native microbes is crucial for understanding their combined effects on plant health and stress resilience. Moreover, there is a pressing need to shift focus towards commercializing endophyte products and implementing them at the field scale, thereby translating research findings into tangible benefits for sustainable agriculture.

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