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# Endophytes: A Natural Solution for Food Safety and Reduced Waste

**Meena Barupal[1] and Sunita Arora[1]**
[1]Department of Botany, Jai Narain Vyas University Jodhpur, Rajasthan
*Corresponding Author: meena.barupal@gmail.com and jnvusunitarora@gmail.com

**Abstract**

Endophytes, microorganisms residing within plant tissues, offer promising natural alternatives to chemical preservatives for food preservation. These beneficial microbes, particularly bacterial and fungal endophytes, produce bioactive secondary metabolites with potent antimicrobial properties, enhancing the shelf life and safety of food products. By preventing the growth of spoilage organisms and pathogens, endophytes reduce the reliance on synthetic chemicals, addressing concerns over environmental and health impacts. Their ability to act as biocontrol agents, coupled with their contribution to nutrient enhancement and plant growth promotion, underscores their multifaceted role in sustainable agriculture and food security.

**Keyword:** Antimicrobial activity, Food preservation, Biocontrol

## Introduction

The food industry faces a constant battle against food spoilage and microbial contamination. Microbial spoilage significantly impacts food waste, with estimates suggesting half of harvested fruits and vegetables in tropical regions are lost due to fungal contamination (Pitt & Hocking, 2009).

Ensuring food safety and minimizing waste are critical for both economic and environmental reasons. While traditional methods like refrigeration and chemical preservatives play a role, there's a growing need for sustainable and natural alternatives. Moreover, the alarming rates of food waste highlight the urgent need for innovative solutions to extend product shelf life and reduce losses throughout the supply chain.

Endophytes, a diverse group of microorganisms residing within plant tissues, have emerged as promising candidates for addressing these challenges. Their capacity to produce a wide array of bioactive compounds, including antimicrobial agents, offers potential for developing natural and effective food preservatives. These natural antimicrobials can help extend food shelf life by inhibiting the growth of harmful bacteria and fungi. This not only enhances food safety but also reduces food waste, contributing to a more sustainable food system.

The nature of endophyte-host interactions can vary from mutualistic to antagonistic or neutral, shaped by evolutionary processes and environmental conditions. Mutualistic symbioses are particularly prevalent, wherein both partners benefit from the association. Endophytes gain a protected environment and nutrients, while plants receive a range of beneficial metabolites that enhance growth and stress tolerance (Khare et al. 2018). Grasses, in particular, harbor endophytes that produce secondary compounds to defend against biotic and abiotic stresses, making them valuable forage for livestock.

## The Diversity and Functions of Endophytes

### Types of Endophytes

Within all plants, a rich diversity of microorganisms exists, encompassing bacterial, archaeal, fungal, and protistic taxa (Hardoim et al. 2015). However, endophytes can be broadly classified into bacterial and fungal endophytes. Bacterial endophytes are the most common and are often associated with the rhizosphere, the soil zone influenced by plant roots. The symbiotic relationship between bacteria and plant induces a range of biochemical and physiological changes beneficial to the host plant, both directly and indirectly. Direct effects include the production of growth regulators, phosphate solubilization, and nitrogen fixation, which contribute to enhanced plant growth. Indirectly, endophytes enhance plant resistance against pathogens, such as through siderophore production, which limits iron availability to phytopathogens. Moreover, bacterial endophytes are renowned for their production of bioactive secondary metabolites, underscoring their potential to improve plant yield and the accumulation of bioactive compounds (Almuhayawi, et al. 2021).

Fungal endophytes, on the other hand, are known for their ability to produce a wide range of secondary metabolites, which play crucial roles in plant health and defence (Morales-Cedeño et al. 2021). Fungal endophytes are more diverse (Rodriguez et al. 2009). provides insights into the classification, discovery, and identification of fungi, estimating Earth's fungal diversity to range broadly from 1.5 million to 5.1 million species. Among these fungi, at least 1 million species are identified as endophytes (Strobel and Daisy, 2003), highlighting their substantial contribution to fungal biodiversity.

Host-Specific Endophytes Endophytic communities are shaped by the crosstalk between plant hosts and their geographical adaptations. Different populations of the same plant species can harbour unique sets of endophytes, contributing to the diversity of secondary metabolite production. This diversity is exemplified by studies showing that different populations of wild cabbage seeds have unique sets of associated bacteria, and endophytic fungi from various medicinal plants exhibit broad-spectrum antimicrobial properties.

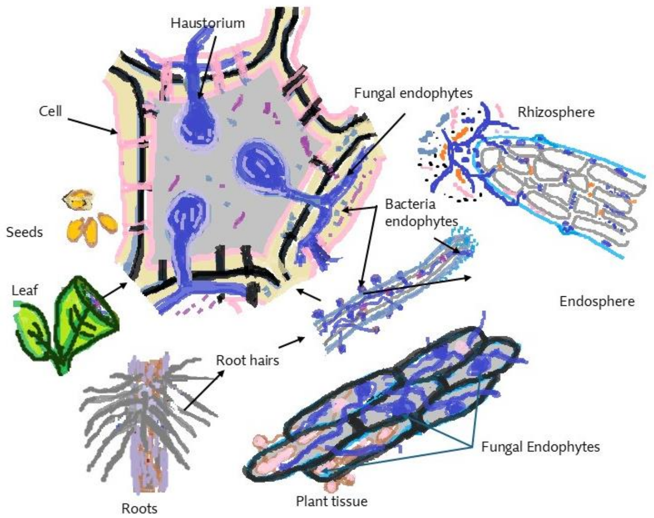


**Fig 1**. Endophytes-plant association: Endophytes become niche specific or may favor global environment. Bacterial endophytes such as Rhizophora root specific bacteria where fungal endophytes localize to almost all part of plants.

**Bioactive Compounds Produced by Endophytes**

Endophytes are recognized for their ability to produce a wide array of secondary metabolites such as phenols, alkaloids, polyketides, quinones, steroids, enzymes, and peptides, exhibiting insecticidal, antioxidant, cytotoxic, antibacterial, antiviral, and anti-malarial properties. These metabolites have garnered significant interest in medicine, agriculture, and industry due to their therapeutic, agricultural, and commercial applications.

A well-known example is taxol, initially isolated from the Pacific yew tree's bark and later found to be produced by the endophytic fungus *Taxomyces andreanae*. This highlights endophytes' potential as a rich source of novel bioactive compounds. Other examples include polyphenols, expansols (cytotoxic compounds from *Penicillium expansum* in *Excoecaria agallocha*), volatile organic compounds with antifungal and antibacterial activities (produced by *Muscodor albus* in *Cinnamomum zeylanicum*), and paclitaxel (an anticancer compound from *Pestalotiopsis microspora* in *Taxus wallichiana)* (in barupal et al. 2024).

Host plants infected with endophytes tend to produce more bioactive compounds compared to those infected with pathogenic endophytes, as endophytes face competition from epiphytes, pathogens, and host defence systems. Recent studies suggest that endophytes acquire genes from host plants for bioactive production. Epigenetic modification and activation of silent biosynthetic pathways can enhance the production of endophyte-sourced secondary metabolites.

**Endophytes in Biocontrol and Disease Management**

**Biocontrol Agents**

Endophytes play a crucial role in plant health by providing resistance to multiple stresses, including drought, nutrient deficiency, and pathogen pressure. They act as biocontrol agents, producing secondary metabolites that help plants cope with various pathogens, including bacteria, fungi, and others. This potential has led to a growing interest in microbial agents with antifungal activities, such as bioprotective cultures, fermenters, and purified molecules, as alternatives to chemical preservation methods.

**Pre-Harvest and Post-Harvest Applications**

The suppression of plant pathogens by PGPB and PGPBE (plant growth-promoting bacterial endophytes) can occur during pre-harvest or post-harvest periods. Pre-harvest applications include prophylactic actions to eliminate potential pathogens residing in the soil and the inoculation of biocontrol agents during planting and plant development. Post-harvest applications focus on preventing the growth of spoilage and pathogenic microorganisms on harvested fruits and vegetables.

**Mechanisms of Disease Suppression**

The mechanisms by which endophytes suppress plant pathogens include competition for space and nutrients, antibiosis, lytic enzyme production, toxin inhibition, and induction of plant defence mechanisms. These strategies help prevent or inhibit the growth of phytopathogens, thus promoting plant health and growth. For example, the antifungal activity of endophytic bacteria isolated from healthy tomatoes against *Alternaria solani,* the causative agent of early blight, demonstrates the potential of endophytes in disease management (Attia et al. 2020).

## Enhancing Nutritional Quality and Shelf Life of Crops

### Nutritional Value of Crops

Endophytes have the potential to enhance the growth and nutritional value of crops. Plants grown in symbiosis with beneficial endophytes exhibit improved growth, enhanced stress tolerance, and increased resistance to diseases. These factors contribute to the production of healthier and more robust crops with enhanced nutritional profiles. For instance, the use of endophytes in the sprouts of *Chenopodium* spp. has been shown to enhance their nutritional value and provide antibacterial activities against pathogenic bacteria.

### Extending Shelf Life

Food storage for long-term use is a significant challenge for the food industry, often requiring substantial investments. Endophytes can play a role in extending the shelf life of food products by preventing the growth of spoilage and pathogenic bacteria or fungi. Endophytes produce bioactive compounds such as antibiotics, enzymes, and volatile organic compounds (VOCs) that exhibit antimicrobial properties against spoilage and pathogenic microorganisms (Huang et al. 2021). These compounds inhibit the growth of bacteria and fungi responsible for food spoilage, thereby preserving the quality and freshness of food items. Endophyte-derived compounds such as chitosan, cellulose derivatives, and polysaccharides have inherent antimicrobial properties. They create a barrier that inhibits the growth of spoilage and pathogenic microorganisms on food surfaces, thereby extending shelf life. For instance, endophyte fungi can be explored to produce polysaccharide-based coatings with antimicrobial properties to extend the shelf life of packed food products. These coatings have antimicrobial properties and create a barrier that reduces oxygen permeability and moisture loss, crucial factors in extending the shelf life of perishable foods like fruits and vegetables (Shariati et al. 2024).

### Advances in Endophytes for Food Packaging

Recent advances in utilizing endophytes for food packaging have focused on their potential to enhance food safety, extend shelf life, and reduce environmental impact. Edible coatings derived from endophytes can regulate moisture levels and oxygen permeability, which are critical factors affecting food quality and preservation. This helps maintain the freshness and texture of perishable foods like fruits and vegetables. Unlike synthetic packaging materials, endophyte-based coatings are biodegradable and environmentally friendly. They contribute to reducing plastic waste and pollution associated with conventional packaging materials. Endophytic metabolites, such as phenolic compounds and flavonoids, exhibit antioxidant properties. These compounds scavenge free radicals and inhibit lipid oxidation, thereby preserving the sensory attributes and nutritional quality of packaged foods. Some endophyte-derived compounds enhance the flavour and aroma of packaged foods, providing a natural alternative to synthetic flavour enhancers (Abrahão et al. 2013).

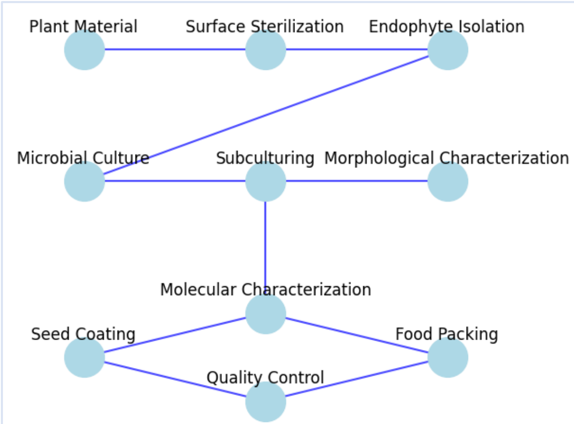


**Fig 2**: A suggested scheme for extraction and purification process of endophytes for food packing and seed coating.

### Integration of AI in Harnessing Endophytes for Food Preservation

The integration of artificial intelligence (AI) with endophytic research holds promise for advancing food preservation strategies. AI technologies can accelerate the discovery and characterization of novel endophytic strains, optimize their application in agriculture, and predict their interactions with host plants and environmental conditions (Ngolong et al. 2024). Machine learning algorithms analyse large datasets to identify optimal endophytes for specific agricultural needs, enhancing the precision and efficiency of biocontrol and plant growth promotion strategies. By using AI, food industries can unlock the full potential of endophytes to improve food quality, reduce spoilage, and enhance sustainability in food production systems. This convergence of biotechnology and AI represents a transformative approach in addressing global food security challenges.

### Regulatory Considerations and Commercialization

As endophyte-based food packaging technologies advance, regulatory agencies are evaluating their safety and efficacy (Jiang et al. 2023).

**Safety Assessments**: Regulatory bodies assess the safety of endophyte-derived compounds used in food packaging to ensure they meet stringent health and environmental standards.

**Commercialization:** Companies are investing in scaling up production and commercializing endophyte-based packaging solutions (Bizongo (blog) 2024). Partnerships between academia, industry, and government facilitate the translation of research findings into market-ready products.

## Conclusion

The role of endophytes in enhancing plant growth and health is versatile and holds great promise for sustainable agriculture. Through the production of bioactive compounds, enhancement of soil fertility, biocontrol of pathogens, and improvement of crop nutritional quality and shelf life, endophytes offer innovative solutions to contemporary agricultural challenges. Further research and development in this field can lead to more effective and environmentally friendly agricultural practices, ultimately benefiting both farmers and consumers.

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