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ENDOPHYTIC MICROORGANISMS OF PLANTS AND THEIR SIGNIFICANCE

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Abstract
This article examines the characteristics of endophytic microorganisms, their role in the formation and functioning of the plant microbiome, and the nature of interactions between endophytes and their host plants. Particular attention is paid to endophytic bacteria and microscopic fungi capable of colonizing the internal tissues of healthy plants without causing pronounced disease symptoms. The main physiological and biochemical mechanisms underlying the beneficial effects of endophytes on plants are considered, including the synthesis of phytohormones, atmospheric nitrogen fixation, mobilization of phosphorus and other mineral nutrients, production of antimicrobial compounds, and activation of plant defense mechanisms. The potential of endophytic microorganisms to enhance plant resistance to biotic and abiotic stress factors is also analyzed. The prospects for the practical application of endophytes in agriculture, biotechnology, sustainable agriculture, and biological plant protection are highlighted.

Keywords: Endophytic microorganisms, endophytic bacteria, endophytic fungi, plant microbiome, plant–microorganism interaction, phytohormones, biological control, phytopathogens, plant resistance, biotechnology.

Introduction

Plants are constantly interacting with numerous microorganisms inhabiting the soil, rhizosphere, plant surfaces, and internal plant tissues. These microorganisms can have both beneficial and detrimental effects on plant growth and

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development. Among them, endophytic microorganisms occupy a special place because they are capable of living within plant tissues without causing pronounced disease symptoms.

The term "endophyte" is derived from the Greek words endon, meaning "within," and phyton, meaning "plant." In a broad sense, endophytes are microorganisms that colonize the internal tissues of plants and exist in close ecological association with their host plants.

Endophytic microorganisms can be found in roots, stems, leaves, seeds, fruits, and other plant organs. Their distribution depends on the species of microorganism, the host plant species, environmental conditions, and the specific characteristics of the interaction between the partners.

The study of endophytic microorganisms has become particularly relevant due to the need to develop environmentally friendly approaches to increasing plant productivity and reducing the dependence of agriculture on chemical fertilizers and pesticides.

Main Groups of Endophytic Microorganisms

The endophytic community of plants comprises a wide diversity of microorganisms. The most extensively studied groups include bacteria and microscopic fungi.

1.1. Endophytic Bacteria

Endophytic bacteria are capable of entering internal plant tissues and establishing stable associations with their host plants. Among the most frequently studied bacterial genera are Bacillus, Pseudomonas, Burkholderia, Enterobacter, Pantoea, Azospirillum, Rhizobium, and Streptomyces.

Many representatives of these genera possess plant growth-promoting properties. They can synthesize biologically active compounds, participate in the mobilization of essential nutrients, and suppress the development of phytopathogenic organisms.

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1.2. Endophytic Fungi

Endophytic fungi are also widely distributed among plants. They can colonize intercellular spaces and internal plant tissues, forming various types of interactions with their host plants.

Some endophytic fungi are capable of synthesizing secondary metabolites that may have beneficial effects on plants or inhibit the development of pathogenic organisms. In some grass species, endophytic fungi of the genus Epichloë can increase plant resistance to herbivores through the production of specific secondary metabolites.

Endophytic microorganisms interact with plants through a complex system of physiological, biochemical, and molecular mechanisms. These interactions can affect plant growth, mineral nutrition, metabolism, defense responses, and adaptation to unfavorable environmental conditions. Depending on the species and functional properties of the microorganism, endophytes may act as plant growth promoters, biological control agents, stress protectors, or producers of biologically active compounds. The main mechanisms through which endophytic microorganisms influence plants are summarized in Table 1.

Table 1. Main Mechanisms of Interaction Between Endophytic Microorganisms and Plants

Group/Mechanism	Main Processes	Effects on the Plant	Practical Significance
Endophytic bacteria	Synthesis of IAA, gibberellins, and cytokinins	Stimulation of root and shoot growth	Increased plant growth and productivity
Nitrogen-fixing endophytes	Biological fixation of atmospheric nitrogen	Improved nitrogen nutrition	Reduced dependence on nitrogen fertilizers
Phosphate-solubilizing microorganisms	Solubilization of poorly soluble phosphates	Increased phosphorus availability	Improved mineral nutrition
Siderophore-producing bacteria	Iron chelation and transport	Improved Fe availability	Increased plant resistance and growth

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Antagonistic bacteria and fungi	Production of antibiotics and antimicrobial compounds	Suppression of phytopathogens	Biological plant protection
Defense response inducers	Activation of systemic resistance	Increased resistance to diseases	Reduced damage caused by phytopathogens
Stress-protective endophytes	Regulation of water and ion balance and antioxidant systems	Increased tolerance to drought and salinity	Application under stressful environmental conditions
Endophytic fungi	Synthesis of secondary metabolites	Plant protection and modification of plant physiology	Biotechnological value
Endophytes of medicinal plants	Synthesis of enzymes and secondary metabolites	Increased diversity of plant metabolites	Pharmaceutical and biotechnology industries

Endophytic microorganisms influence plants through a variety of physiological and biochemical mechanisms. One of the most important mechanisms is the production of phytohormones, such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, which stimulate root and shoot development. Nitrogen-fixing endophytes contribute to plant nutrition by converting atmospheric nitrogen into forms that can be utilized by plants, while phosphate-solubilizing microorganisms increase the availability of phosphorus in the rhizosphere and plant tissues.

Siderophore-producing microorganisms improve iron acquisition by binding iron and facilitating its uptake. In addition, antagonistic endophytes can produce antimicrobial compounds that inhibit phytopathogenic microorganisms. Some endophytes activate the plant's defense system and induce systemic resistance, thereby increasing resistance to diseases. Other endophytic microorganisms enhance tolerance to drought, salinity, and oxidative stress by regulating water balance, ion homeostasis, and antioxidant activity.

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Endophytic fungi are particularly important due to their ability to produce diverse secondary metabolites. In medicinal plants, these microorganisms may contribute to the biosynthesis or modulation of biologically active compounds, making them promising sources for pharmaceutical and biotechnological applications.

The practical significance of endophytic microorganisms is determined by their ability to improve plant growth, nutrition, resistance, and adaptation to unfavorable environmental conditions. Due to their diverse physiological and biochemical activities, endophytic bacteria and fungi are considered promising biological resources for modern agriculture, biotechnology, and biological plant protection.

Endophytic microorganisms can be used as biological agents to stimulate plant growth and development. The production of phytohormones, including indole-3-acetic acid, gibberellins, and cytokinins, as well as the mobilization of essential nutrients, can contribute to the development of the root system and improve the overall physiological condition of plants. Nitrogen-fixing and phosphate-solubilizing endophytes are particularly important because they can improve the availability of nutrients and potentially reduce the need for chemical fertilizers.

Another important area of application is biological plant protection. Many endophytic microorganisms produce antimicrobial compounds, siderophores, hydrolytic enzymes, and other biologically active substances that can inhibit phytopathogenic microorganisms. Some endophytes are also capable of activating plant defense mechanisms and inducing systemic resistance, thereby increasing plant resistance to diseases and reducing the need for chemical pesticides.

Endophytes are also of considerable interest in the development of environmentally sustainable technologies for plants exposed to drought, salinity, temperature fluctuations, and other abiotic stresses. By regulating water and ion balance, antioxidant systems, and other physiological processes, endophytic microorganisms may contribute to maintaining plant growth under unfavorable environmental conditions.

Particular attention is currently being paid to endophytes associated with medicinal plants. These microorganisms can synthesize enzymes, antibiotics, pigments, and various secondary metabolites with potentially valuable biological

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properties. Such compounds may be of interest to the pharmaceutical, food, cosmetic, and biotechnology industries.

Thus, the practical application of endophytic microorganisms provides opportunities for the development of biofertilizers, biostimulants, biological plant protection products, and other environmentally friendly technologies. Their use may contribute to increasing crop productivity, improving plant resistance, reducing the excessive application of agrochemicals, and promoting the principles of sustainable agriculture.

Conclusion

Endophytic microorganisms are an important component of the plant microbiome and play a significant role in plant growth, nutrition, defense, and adaptation to environmental stresses. Through the production of phytohormones, mobilization of nutrients, synthesis of antimicrobial compounds, and activation of plant defense mechanisms, endophytic bacteria and fungi can positively influence the physiological state of their host plants.

Their diverse functional properties highlight the considerable potential of endophytes for sustainable agriculture, biological plant protection, biotechnology, and the production of biologically active compounds. Further study of plant–endophyte interactions will contribute to the development of environmentally friendly technologies aimed at improving plant productivity and resistance.

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