"UNRAVELING THE INTRICATE DANCE: EXPLORING THE DYNAMIC RELATIONSHIP BETWEEN PLANTS AND MICROBES IN THE PLANT MICROBIOME – A MINI REVIEW"

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Abstract
Plant-microbe interactions and the plant microbiome play a critical role in shaping plant growth, health, and productivity. This review provides a comprehensive review of current knowledge on the topic, including the dynamics of plant-microbe interactions, the composition and functions of the plant microbiome, and its impact on various aspects of plant growth and health. The mutualistic relationships between leguminous plants and nitrogen-fixing rhizobia bacteria, and between plants and arbuscular mycorrhizal fungi, are discussed, as well as parasitic relationships between plants and microorganisms. The impact of the plant microbiome on nutrient acquisition and uptake, defense against pathogens, stress tolerance, and plant hormone regulation is also explored. The review concludes by highlighting the potential for further exploration and discovery in this exciting area of research and its implications for improving crop productivity and sustainability.

Keywords: Plant-microbe interactions, Plant microbiome, Growth and health, Nutrient acquisition, Pathogen defense, Stress tolerance, Plant hormone regulation and Crop productivity and sustainability.

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Introduction

Plants have a close association with microorganisms, which can have a profound impact on plant growth, health, and productivity (Das et al., 2022). The plant microbiome refers to the complex community of microorganisms that colonize plant surfaces and roots, and play a crucial role in shaping plant development and adaptation to changing environmental conditions (Trivedi et al., 2022; Ali et al., 2022 and Sandrini et al., 2022). In recent years, there has been a growing body of evidence demonstrating that microorganisms play a key role in regulating various aspects of plant growth and nutrition.

Plant-microbe interactions*:* Plant-microbe interactions are dynamic and can be either symbiotic or parasitic (Fields and Friman, 2022). The most well-known symbiotic relationship is that between leguminous plants and nitrogen-fixing rhizobia bacteria. Rhizobia colonize the roots of legumes and form nodules, where they fix atmospheric nitrogen into a form that can be used by the plant (Wendlandt et al., 2022 and Ashrafi et al., 2022). This symbiotic relationship benefits both partners, as the plant provides a source of energy for the bacteria, and the bacteria provide the plant with a source of nitrogen (Aziz et al., 2022). Another type of symbiotic relationship is the mutualistic association between plants and arbuscular mycorrhizal fungi (Sangwan and Prasanna, 2022), where the fungus forms a symbiotic relationship with plant roots and provides the plant with phosphorous and other nutrients in exchange for photosynthetically-fixed carbon. In contrast, parasitic relationships between plants and microorganisms result in the colonization of plant tissues and the extraction of nutrients from the plant host, resulting in plant disease and reduced growth (Liu et al., 2022)

The plant microbiome and its impact on plant growth and health*:* The plant microbiome is a complex community of microorganisms that colonize plant surfaces and roots, and play a crucial role in shaping plant development and adaptation to changing environmental conditions. The plant microbiome can impact plant growth and health in various ways, including:

Nutrient acquisition and uptake: Microbes play a crucial role in plant nutrient acquisition and uptake by breaking down complex organic matter into simpler forms that can be readily absorbed by plants (Mitra et al., 2022). The primary function of microbes in this process is to decompose organic matter and recycle nutrients, making them available for plant uptake (Soong et al., 2020; Yadav et al., 2021). In order for plants to thrive, they need a variety of essential nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (Kirkby, 2023). These nutrients are often present in the soil in complex organic forms that are not immediately available for plant uptake (Havlin, 2020). This is where microbes come in. Microbes, such as bacteria, fungi, and actinomycetes, play a key role in breaking down complex organic matter into simpler forms that plants can absorb (Ibadin, 2021). For example, nitrogen-fixing bacteria can convert atmospheric nitrogen gas into a form that plants can use. This process is called nitrogen fixation, and it is essential for plant growth and development (Mahmud et al., 2020). In addition to nitrogen fixation, microbes also play a crucial role in phosphorus acquisition. Phosphorus is an essential nutrient for plant growth, but it is often present in the soil in an insoluble form (Janati et al., 2021; Elhaissoufi et al., 2022; Daniel et al., 2022). Mycorrhizal fungi are specialized fungi that form symbiotic relationships with plant roots. They can help plants acquire phosphorus by releasing enzymes that break down phosphorus-containing compounds, making them available for plant uptake (Lambers, 2022). Another way in which microbes aid in plant nutrient acquisition is through the production of plant growth-promoting hormones. These hormones can stimulate plant growth and development, and they are produced by a variety of microorganisms such as bacteria and fungi (Orozco-Mosqueda et al., 2021). Microbes can also help plants acquire nutrients by increasing the solubility of minerals in the soil. For example, certain bacteria can produce organic acids that can dissolve minerals such as calcium and magnesium, making them more readily available for plant uptake (Amarasinghe et al., 2022).

Defense against pathogens: Microorganisms can produce antimicrobial compounds that protect the plant from pathogens, and some microorganisms can directly compete with pathogens for nutrients and space (Amaning Danquah et al., 2022 and Tyśkiewicz et al., 2022). Microbes, including rhizobia, mycorrhizal fungi, and root-associated bacteria, can form symbiotic relationships with plants, providing them with essential nutrients and stimulating their growth (Liu et al., 2021). In return, plants provide microbes with a habitat and nutrients, creating a mutualistic relationship (Prasad et al., 2021). Microbes can also play a role in plant defense against pathogens by colonizing plant roots and competing with pathogens for nutrients and space, thereby reducing their ability to establish infections (Santoyo et al., 2021; Poveda et al., 2020). Root-associated bacteria are known to secrete antibiotics, such as bacteriocins, that inhibit the growth of pathogens (boro et al., 2022). For example, rhizobia secrete bacteriocins that have been shown to inhibit the growth of pathogens such as Salmonella typhimurium and Escherichia coli (Telhig et al., 2020). Similarly, mycorrhizal fungi can produce antifungal compounds, such as chitinases and glucanases, which can degrade fungal cell walls and reduce the ability of fungi to cause infections (Tanaka and Kahmann, 2021; Tyśkiewicz et al., 2022). One of the primary mechanisms of microbial-mediated plant defense is the production of antimicrobial compounds (Shahrtash and Brown, 2021). Root-associated bacteria can secrete antibiotics, such as bacteriocins, that inhibit the growth of pathogens (Nazari and Smith, 2020). Another mechanism of microbial-mediated plant defense is the stimulation of plant defense responses, such as the production of phytohormones, the activation of plant defense genes, and the reinforcement of cell walls (Bonini et al., 2020; Dini-Andreote, 2020). For example, mycorrhizal fungi have been shown to stimulate the production of phytohormones, such as salicylic acid and jasmonic acid, which activate plant defense responses and reinforce cell walls (Ambarwati et al., 2022).

***Stress tolerance*:** Microorganisms can help plants adapt to environmental stress, such as drought, salinity, and extreme temperatures (Phour, and Sindhu, 2022). Plants are constantly exposed to various environmental stress factors, such as drought, high salinity, extreme temperatures, and oxidative stress that negatively affect their growth and productivity (Hasanuzzaman et al., 2012; Mareri et al., 2022). However, many plants have developed various mechanisms to mitigate the effects of stress and maintain their growth and survival. Microbes play a crucial role in enhancing the stress tolerance of plants. Many plants have developed symbiotic relationships with microbes, such as rhizobia and mycorrhiza, which help them to tolerate various environmental stressors (Sharma et al., 2020). These microbes can produce metabolites and signaling compounds that influence the plant's stress response and enhance its stress tolerance (Liu et al., 2020). Rhizobia, for example, are nitrogen-fixing bacteria that form a symbiotic relationship with legume plants, such as beans and peas. This symbiosis benefits both partners, as the bacteria provide the plant with fixed nitrogen in exchange for plant sugars (Mahmud et al., 2020). In addition, rhizobia also help legume plants to tolerate abiotic stress factors, such as drought and high salinity, by producing compounds that enhance the plant's stress tolerance (Sharma et al., 2020; Sindhu et al., 2020). Mycorrhiza, on the other hand, is a symbiotic relationship between fungi and plant roots (Hoang et al., 2022). This symbiosis benefits the plant by improving its nutrient uptake, especially phosphorous, and enhancing its tolerance to various abiotic stress factors (Thangavel et al., 2022; Khaliq et al., 2022). Mycorrhiza fungi can produce compounds that scavenge reactive oxygen species (ROS), protect plant cells from oxidative damage, and enhance plant tolerance to various stress factors (Zhang et al., 2022; Liu et al., 2022; Branco et al., 2022). In addition to these symbiotic relationships, some microbes can also induce systemic acquired resistance (SAR) in plants (Kamle et al., 2020). SAR is a plant's defense mechanism against biotic and abiotic stress factors, triggered by the presence of microbes (Zehra et al., 2021). These microbes can produce signaling compounds that activate the plant's stress response, leading to the production of phytohormones, ROS, and other defense compounds that enhance the plant's stress tolerance (Tiwari et al., 2020; Zehra et al., 2021). In conclusion, microbes play a crucial role in enhancing the stress tolerance of plants by producing compounds and signaling pathways that help the plant to cope with various environmental stress factors. This symbiotic relationship benefits both partners and enhances the overall productivity and sustainability of plant systems.

Plant hormone regulation: Microorganisms can produce phytohormones, such as auxins and gibberellins that regulate plant growth and development (Orozco-Mosqueda et al., 2023). Plants are sessile organisms that are dependent on hormones for various growth and developmental processes. Hormones such as auxins, gibberellins, cytokinins, abscisic acid, and ethylene regulate various processes in the plant such as cell division, elongation, differentiation, stress response, and others (Mukherjee et al., 2022; Asif et al., 2022; Vaishnav and Chowdhury, 2022). The role of microbes in plant hormone regulation has been a subject of interest in recent years, and researchers have found that microbes can influence plant hormone levels, thus modulating plant growth and development (Orozco-Mosqueda et al., 2023 and Moon and Ali, 2022). Auxins are involved in apical dominance, root initiation, and root growth. They are involved in the regulation of elongation and differentiation of cells (García-Cárdenas et al., 2022 and Roychoudhry and Kepinski, 2022). The presence of certain rhizobacteria, such as Azospirillum brasilense, has been shown to increase auxin levels in the plant and promote root growth (Turan et al., 2021; Méndez-Gómez et al., 2021 and Zaheer et al., 2022). Gibberellins are involved in seed germination, stem elongation, and the regulation of flowering (Zhang et al., 2022). Some fungi, such as Fusarium oxysporum, have been shown to produce gibberellins and promote stem elongation in plants (Desjardins et al., 2000; Hasan, 2002 and Fatima et al., 2023). Cytokinins are involved in cell division, differentiation, and root growth (Svolacchia and Sabatini, 2023). Some rhizobacteria, such as Rhizobium leguminosarum, have been shown to produce cytokinins and promote root growth in plants (Swarnalakshmi et al., 2020). Abscisic acid is involved in the regulation of stress responses, seed dormancy, and fruit maturation (Parwez et al., 2022). Some microbes, such as the bacterium Xanthomonas campestris, have been shown to produce abscisic acid and induce stress responses in plants (Xu et al., 2013). Ethylene is involved in the regulation of fruit ripening, flower senescence, and stress responses (Kolbert et al., 2020). Some microbes, such as the fungus Botrytis cinerea, have been shown to produce ethylene and induce stress responses in plants (Chagué et al., 2006). In conclusion, microbes play a crucial role in plant hormone regulation by modulating the levels of hormones such as auxins, gibberellins, cytokinins, abscisic acid, and ethylene, thereby influencing various growth and developmental processes in the plant. Understanding the interplay between plants and microbes can provide insight into improving crop yields and promoting sustainable agriculture practices.

Conclusion

The plant microbiome is a complex and dynamic community of microorganisms that play a crucial role in shaping plant growth, health, and productivity. A deeper understanding of plant-microbe interactions and the impact of the plant microbiome on various aspects of plant growth and health has the potential to revolutionize our understanding of plant biology and lead to the development of new strategies for improving crop productivity and sustainability. This area of research holds great promise for the future and is an exciting area for further exploration and discovery.

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