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Review Article

EXPLORING THE MULTIFACETED INTERACTIONS BETWEEN MICROBES AND PLANTS FOR ENHANCING PLANT HEALTH, COMBATTING DISEASES, AND MITIGATING ABIOTIC STRESS

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Abstract *Arbuscular mycorrhizal fungi (AMFs) are highlighted for their beneficial effects on plant development and stress tolerance. Plant-growth-promoting microorganisms (PGPMs), including various bacterial and fungal species, are identified as key players in enhancing plant growth, nutrient absorption, and disease resistance. The interactions between plants and soil microbes, such as nutrient mobilization and disease prevention, are explored in detail. The article emphasizes the importance of understanding plant-microbe interactions for developing sustainable agricultural practices. It discusses the potential of beneficial microorganisms, such as biological control agents (BCA) and plant-growth-promoting rhizobacteria (PGPR), in improving crop productivity and disease management. The molecular mechanisms underlying plant defense responses and microbial interactions are investigated to develop innovative crop protection strategies. Furthermore, the review article delves into the role of microorganisms in mitigating abiotic stresses, such as salt, drought, and pollution. Plant Growth Promoting Bacteria (PGPB) are highlighted for their ability to enhance nutrient absorption, nitrogen fixation, and resistance to salt stress through induced systemic tolerance (IST). Phytoremediation techniques, which utilize bacteria coexisting with plants to remove organic contaminants and heavy metals from soils, are also discussed. Overall, the review article underscores the significance of plant-microbe interactions in agriculture and environmental remediation. It calls for further research to elucidate the complex mechanisms underlying these interactions and to develop effective strategies for harnessing the potential of beneficial microorganisms in promoting plant growth, nutrient uptake, and stress tolerance.*

Keywords: *Plant microbiomes; rhizosphere bacteria; arbuscular mycorrhizal fungi; plant-growth-promoting microorganisms; soil microorganisms; plant-microbe interactions*

Introduction

The food crisis has become a severe issue as the world's population grows and food production resources decline. One of the primary causes of this problem is the loss of fertile farmland due to a combination of factors such as deforestation, soil degradation, flooding, salinity, and heavy metal stress. Human action is another factor that influences outcomes. Crop productivity is expected to improve from 60% to 100% by 2050 to feed the world's 9.7 billion inhabitants. However, given the condition of climate change and current agricultural methods, it is improbable that this target will be achieved (Lee et al., 2023). Salinity in the soil reduces plant development and yield, and decreased productivity in agricultural areas affects agribusinesses as well (Wadgymar et al., 2017). Microorganisms such as plant-growth-promoting fungi and rhizobacteria reduce abiotic stress. Beneficial microorganisms moderate abiotic stress through a variety of ways, including the production of phytohormones, the lowering of ethylene oxide levels, the stimulation of genes encoding antioxidant genes, and the enhancement of the dehydration response. Bacteria in plant roots frequently secrete phytohormones, which reduce salinity and inhibit seedling growth (Sagar et al., 2021). Certain research has shown that activating primary metabolisms by microorganisms under abiotic stress improves plant growth,

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photosynthesis, nutrient absorption, and antioxidant enzyme activity. Secondary metabolites that help with abiotic stress tolerance include flavonoids, phytoalexins, phenylpropanoids, and carotenoids. In the presence of abiotic stress, both fungal and bacterial species promote secondary metabolite synthesis (Ma et al., 2019). Using plant growth-promoting rhizobacteria (PGPRs) from manure is another promising technique for reducing the negative effects of abiotic stress, promoting plant development, eliminating heavy metals, and counteracting pesticides. Several modern strategies, such as the use of beneficial microorganisms, can boost agricultural yields. These microorganisms have the potential to increase agricultural output by promoting phytohormone production, nitrogen fixation, and tolerance to biotic and abiotic stress (Hartman and Tringe, 2019).

Microbes Associated with Plants

Plant microbiomes, which consist of bacteria present in the rhizosphere, leaves, and other plant tissues, have a favorable impact on plant physiology and growth. Environmental circumstances determine the function and makeup of the plant microbial population. Certain mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMFs), cohabit peacefully with terrestrial plants, such as halophytes, which can develop hyphae and vesicles in their roots and sporulate in the rhizosphere. By providing superior access to soil surface area, AMFs promote plant development and nourishment (Bouasria et al., 2012).

AMFs also aid in buffering abiotic stresses by increasing mineral acquisition, improving water uptake, ionic balance, phytohormone synthesis, increasing photosynthetic activity, and producing more antioxidant enzymes. Increased Na^+ and Cl^- ratios in the soil can limit plant development and biomass, alter nutrition ratios, and impede critical ion transport. AMFs' enlarged hyphae network in the soil helps plants absorb more water. To maintain cellular osmoregulation, they stimulate the accumulation of osmolytes in plants, enhance aquaporins and water-channel proteins, and promote water transport within plant cells. Higher Na^+ concentrations caused by salinity stress cause plants to lose some of their plasma membrane transporters and absorb fewer nutrients, therefore AMFs can control ionic homeostasis (Schimel, 2018). Under salt stress, AMFs produce auxins and cytokinins, which stimulate plant growth and hormone synthesis. Strong interactions between plants and AMFs may minimize ROS levels. This helps plants cope with salinity stress by increasing the levels of enzymes that protect them from oxidative damage, such as catalase, glutathione reductase, ascorbate peroxidase, superoxide dismutase, and monodehydroascorbate reductase (Ochoa-Hueso et al., 2018).

Role of microbes for enhancing plant health

In the agricultural industry, soil microorganisms have been used for many years to improve soil structure, plant growth, disease management, and nutrient assimilation. They also help to mineralize organic pollutants found in soil. Microorganisms in the rhizosphere secrete chemicals that help plants grow and produce more. By affecting cell division in the shoot, bacteria and fungi that produce phytohormones can cause tumorous growth in plants. Nonetheless, augmenting the consumption of nutrients and water could improve the structure of the roots and shoots (Mathimaran et al., 2020). Sustainable crop production depends on the transformation, mobilization, and solubilization of nutrients from the soil, all of which are influenced by the dynamic interactions between plants and microorganisms in the rhizosphere. PGPRs, also known as plant-health-promoting rhizobacteria (PHPRs) or nodule-promoting rhizobacteria (NPRs), function by creating a hospitable soil milieu in the rhizosphere that promotes plant-microbe interaction. PGPRs are divided into two groups based on how they interact with plants: symbiotic (iPGPRs) and free-living (ePGPRs) (Asghari et al., 2020).

PGPRs aid in the creation of sustainable agricultural systems by stimulating chemical synthesis in plants, improving the movement of nutrients from soil to plants, and preventing plant diseases. These organisms target phytopathogenic bacteria with an antagonistic action and generate phytohormones such as auxin, IAA, abscisic acid (ABA), gibberellic acid (GA), and cytokinins. PGPRs strengthen the nutrients' resilience to oxidative stress, salinity, and drought by facilitating the minerals' mineralization and dissolution. Furthermore, they aid in the synthesis of water-soluble vitamins such as niacin, thiamine, riboflavin, and biotin (Lopes et al., 2018). Plant-growth-promoting microorganisms (PGPMs) are bacterial and fungal species that help plants grow and develop by reducing the effects of both biotic and abiotic stressors. Among these microbes are Streptomyces, Eneterobacter, Flavobacterium, Pseudomonas, Rhizobium, Frankia, Clostridium, Trichoderma, Beauveria, and Serratia. PGPMs are biofertilizers that help plants absorb nutrients more effectively by solubilizing elements of the soil such as phosphorous and potassium. They also serve as biocontrol and biopesticide agents, strengthening resistance to phytopathogens (Czarnes et al., 2020).

Plants and soil microbes interact in a variety of ways, such as by reducing abiotic stressors and avoiding plant diseases. Microbes were not recognized as root symbionts until the nineteenth century. A few bacterial cultures were applied to agricultural

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seedlings to aid in growth and development. Furthermore, bacterial species called Azospirillum and Pseudomonas support the growth of plants (Gyaneshwar et al., 2011; Shayanthan et al., 2022).

By facilitating the digestion of nutrients found in the soil, releasing necessary chemicals needed for plant nutrition, and mobilizing nitrogen sources, bacteria can enhance the nutrient content of plants. Since nitrogen-fixing bacteria are frequently found in non-leguminous plants, the presence of nitrogenase genes in bacterial taxa may be beneficial to plants. Reintroducing growth-promoting microbial strains to plants by the use of specific fungi, such as Glomus intraradical, that may transport organic nitrogen to the plants is a common method in agriculture (Roberts et al., 2010). The mineralization of organic phosphorous compounds and the solubilization of inorganic phosphorus are processes that include several species of bacteria and fungi. Pseudomonas strains are employed to promote the growth of sulphur. Plant-associated bacteria have the potential to stimulate plant growth, but more research is needed to fully comprehend their interactions and how they impact the growth and nutritional makeup of plants (Guo et al., 2020; Shayanthan et al., 2022).

Role of microbes for combating diseases

Plant pathology has shown that plants can detect infections and that pathogen species differ in their sensitivity and resistance. Host plants infect and invade other plants' tissues or organs, whereas non-host plants have a hypersensitivity reaction (HR) when their tissues are pierced (Bonaterra et al., 2022). Plants have two types of defence mechanisms: constitutive and inducible. Constitutive reactions consist of pre-existing biochemical defences or general barriers. Induced reactions, which can be systemic or localized, include gene expression, signal transduction, and pathogen recognition by the host plant. In contrast to systemic defence, which involves signals from the site of interaction in response to chemicals, bacteria, insects, mechanical damage, or stress, localised responses involve programmed cell death. Plants' inducible defence response produces a limited range of biochemical substances that are not highly specific to the pathogen of interest; however, the specificity stems from the ability to identify intracellularly specific protein types released by the pathogen using an interaction recognition system (Shah et al., 2021). There is experimental evidence that fungi, pathogenic bacteria, and plant viruses all have AVR genes.

The molecular underpinning of plant-microbe interactions is being investigated to develop less intrusive crop protection approaches based on the use of beneficial microorganisms and stimulation of the plant defence response. Beneficial non-symbiotic plant bacteria include biological control agents (BCA) and plant-growth-promoting rhizobacteria (PGPR). These bacteria can form intimate symbiotic partnerships with plants or live in more subdued interactions as endophytes or epiphytes. Effective screening procedures are required for the arduous and ineffective process of isolating PGPR and BCA (Mitra et al., 2023). The PGPR are found in the rhizosphere, which is the area of soil that is directly touched by plant roots. When plants are injected with PGPR, their root system and overall growth improve, and certain soilborne plant diseases are often prevented from spreading. The host plant and bacteria play critical roles in the mechanisms that promote plant growth.

BCAs can be found in both the aerial plant and the root system, which supports a diverse microbiota. The majority of these microorganisms provide efficient protection against fungi and bacteria that cause plant disease. Meanwhile, few of these isolates show sufficient biological activity in food or the field (Omidvari et al., 2023). The dose-dependent practical application of PGPR or BCA as microbial fertilizers or pesticides is a technical problem that must be addressed at the biotechnological level. The development of acceptable methodologies for industrial scale-up and fermentation, as well as the formulation that will be offered as a commercial biofertilizer or biopesticide, is a technological challenge. A new class of chemical substances has evolved, either through biotechnology or chemical synthesis techniques. In vitro, these compounds activate plant defensive responses rather than acting as antimicrobials against infections (Egamberdieva et al., 2023).

Transgenic plants have been developed to improve resistance to a wide range of plant pathogenic bacteria and fungi by overexpressing R genes, PR proteins, or modified genes encoding HR elicitors. To summarize, new disease-control strategies based on a fundamental understanding of plant-microbe interactions and including novel biotechnological products will soon enhance or replace traditional plant disease management methods (Rai et al., 2021).

Role of microbes for mitigation of abiotic stresses

A wide range of stresses, including salt, drought, temperature, alkalinity, and pollution, are significantly reduced by microorganisms. There are direct impacts of rhizobacteria and endophytes, especially Plant Growth Promoting Bacteria (PGPB), on siderophore production, nitrogen fixation, and nutrient absorption. Additionally, they increase plants' resistance to salt stress through induced systemic tolerance (IST) (Gopalakrishnan et al., 2015).

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PGPB strengthens plants' antioxidant system and increases their resistance to abiotic stresses by regulating the amounts of antioxidant enzymes. Through modifications to plant physiology and biochemistry, rhizobacteria that stimulate plant growth enhance situations of water scarcity; this process is referred to as rhizobacterial-induced drought endurance and resilience (RIDER). These methods effectively control the absorption of water and minerals while maintaining plant development, membrane integrity, and enzyme constancy—all of which are factors in the management of plant water deficit—by increasing the surface area of the roots (Kaushal and Wani, 2016).

The detrimental effects of bacteria are lessened when they adapt to high or low temperatures. They can withstand temperature changes while preserving the stability of their membranes and enzymes because their metabolism is controlled by certain enzymatic structures. In reaction to these circumstances, temperature shock and cold shock proteins are generated, offering resistance to high-temperature stress in the vicinity. High-altitude agroecosystems harbour a diverse array of cold-adapted microorganisms that can significantly aid plants in adapting to harsh environmental conditions (Verma et al., 2019). With the use of bacteria that coexist with plants and a synergistic relationship between them, the phytoremediation technique removes organic contaminants that biodegrade and heavy metal-contaminated soils from environments. A multitude of mechanisms, such as bioaccumulation, enzymatic detoxification, metal mobilization, immobilization, volatilization, and EPS complexation, are employed by PGPB in response to heavy metal stress. Since metal pollutants are difficult to break down, microbes have an impact on the solubility and accessibility of metals in soil. By forming complexes, growth-promoting bacteria gather chelating agents like siderophores, which can decrease the pH of the soil and increase its solubility in metals (Burges et al., 2018). The Phyto stabilization of severely metal-polluted soils through growth-promoting microorganisms and plant development may reduce the availability of metals. This might happen through discharge by descent, changed metal adsorption onto plant cell walls, or the synthesis of distinct, metal-specific molecules. A combination of different Phyto-technologies, long-term application, and financial support is known as phyto-management, and it is used to clean up soil contaminated with metals (Ullah et al., 2015).

Conclusion

In conclusion, this review article highlights the importance of plant microbiomes, including bacteria, in plant physiology and growth. It highlights the role of arbuscular mycorrhizal fungi, plant-growth-promoting microorganisms, and phytoremediation techniques in improving crop productivity, disease management, and mitigating abiotic stresses.

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