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Invisible Beneficial Microorganisms: The Underground Workforce Enhancing and Protecting Our Crops

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Abstract

Beneath the soil surface exists a highly active and diverse microbial ecosystem that plays a fundamental role in sustaining agriculture and global food production. Among these microorganisms, plant growth promoting microorganisms (PGPMs), establish close associations with plant roots and significantly influence plant performance. They enhance nutrient acquisition by fixing atmospheric nitrogen, solubilizing phosphorus and other essential minerals, and improving nutrient mobilization in the rhizosphere. In addition, they protect plants from pathogens through competition, antibiosis, enzyme production, and activation of plant defense responses. PGPMs offer an eco-friendly and cost-effective alternative to excessive chemical inputs. By improving soil health, enhancing stress tolerance, and supporting consistent crop productivity, these beneficial microbes contribute to resilient farming systems.

Introduction

Agriculture is vital for sustaining the growing global population, yet crop productivity is increasingly challenged by biotic and abiotic stresses such as climate variability, pathogens, abiotic stresses and declining arable land. Although chemical fertilizers enhance yield, their excessive and prolonged use degrades soil health, disrupts microbial balance, and threatens long-term sustainability. Soil is a dynamic ecosystem that harbors diverse microbial communities, including plant growth promoting microorganisms (PGPMs), which regulate nutrient cycling and support soil structure. Through close interactions with plant roots, these beneficial microbes enhance nutrient availability, stimulate growth, and improve plant resilience against stresses (Figure. 1), highlighting their importance in sustainable agriculture (Singh *et al.*, 2022; Khan *et al.*, 2024).

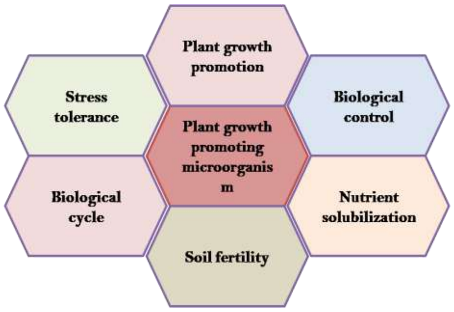

Figure1: Different mechanisms employed by plant growth promoting microorganism to enhance plant growth and health.

Rhizosphere- PGPM Interactions

The rhizosphere is the narrow soil zone influenced by plant roots and serves as an active site for nutrient exchange and microbial activity. It harbors diverse microorganisms that drive key biogeochemical processes thereby supporting soil fertility and plant productivity (Larsen *et al*., 2015). Plant growth-promoting rhizobacteria (PGPR) are beneficial inhabitants of this region that enhance plant performance through multiple mechanisms (Table 1).

Direct Mechanisms in Plant Growth Enhancement and Protection

Rhizosphere microorganisms enhance plant growth through direct mechanisms that improve nutrient acquisition and regulate plant physiology. These beneficial effects are primarily achieved through the following mechanisms: Nitrogen fixation: Certain rhizobacteria convert atmospheric nitrogen (N_2) into plant-assimilable forms such as ammonia (NH_3), improving nitrogen availability in nutrient-deficient soil; Phosphorus solubilization: Phosphate-solubilizing bacteria and mycorrhizal fungi enhance phosphorus bioavailability by solubilizing inorganic phosphates and mineralizing organic forms; Siderophore production: PGPM produce siderophores that chelate iron, increasing its availability to plants and supporting growth; Auxin (IAA) production: Many PGPM synthesize indole-3-acetic acid (IAA), which stimulates root and shoot development, cell elongation, vascular differentiation, and improved root colonization.

Indirect Mechanisms in Plant Growth Enhancement and Protection

Plant growth - promoting microorganisms (PGPMs) enhance plant health indirectly through biological control and stress mitigation strategies that suppress pathogens and strengthen plant defense systems: Competition for nutrients and space: Biocontrol agents compete with pathogens for limited resources such as carbon, nitrogen, oxygen, and ecological niches.

Table 1: Beneficial microorganisms and their associated crops highlighting key functions in plant growth promotion and protection.

Sl. No.	Microorganisms	Plant / Crop	Key Functions in Plant Growth and Protection	References
1.	*Bacillus* and *Paenibacillus* sp.	Maize	Combat of Zn and Fe malnutrition in maize.	Ahmad *et al*., 2024
2.	*Pseudomonas palleroniana* N26 and *Pseudomonas jesenii* MP1	Kidney bean	Enhanced nutrient mobilization, increasing grain yield, protein, and zinc content	Khan *et al*., 2023
3.	*B. ottawaense* SG09 and *Pseudomonas* species	Soybean	Improved biomass and grain yield.	Win *et al*., 2024
4.	*Pseudomonas protegens*	Wheat	Enhanced zinc biofortification under saline stress conditions.	Singh *et al*., 2022

Effective suppression occurs when the antagonist colonizes the rhizosphere efficiently and utilizes resources more effectively than the pathogen; Antibiosis: Certain microorganisms produce antibiotics, toxins, and other inhibitory metabolites that suppress or destroy pathogens. These compounds may be synthesized under varying nutrient conditions and function at low concentrations; Induced systemic resistance (ISR): PGPM can trigger plant defense pathways, activating defense-related enzymes and proteins that enhance resistance against pathogens and insect pests; Abiotic stress tolerance: PGPM improve plant resilience to drought, salinity, heat, and heavy metal stress by modulating phytohormone levels, producing ACC deaminase, siderophores, volatile organic compounds, and protective enzymes.

Conclusion

In conclusion, plant growth promoting microorganisms are an essential yet often under recognized component of agricultural systems. By naturally improving nutrient availability, suppressing plant diseases, and enhancing tolerance to environmental stresses, these beneficial microbes provide a sustainable approach to crop production. Their adoption in farming practices can decrease reliance on synthetic inputs while supporting long-term soil health and food security. The foundation of resilient agriculture may, therefore, depend on the microbial life present in the soil.

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