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Role of Plant Growth-Promoting Rhizobacteria in Improving Soil Health and Sustainable Crop Productivity

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INTRODUCTION

Plant Growth-Promoting Rhizobacteria (PGPR) are a diverse group of beneficial soil bacteria that colonize the rhizosphere i.e. the narrow zone of soil surrounding plant roots and enhance plant growth through a variety of direct and indirect mechanisms. These microorganisms improve nutrient acquisition, synthesize phytohormones, suppress soil-borne pathogens, alleviate abiotic stresses, and stimulate plant defense responses, thereby contributing to improved soil fertility and sustainable crop production. The **rhizosphere** is considered one of the most biologically active regions of soil due to the continuous release of root exudates, including sugars, amino acids, organic acids, vitamins, and secondary metabolites. These compounds create a nutrient-rich microenvironment that supports dense and diverse microbial communities. The interactions between plant roots and rhizosphere microorganisms play a pivotal role in nutrient cycling, organic matter decomposition, disease suppression, and maintenance of soil ecosystem functions.

Beneficial rhizobacteria have become an essential component of sustainable agriculture because they improve nutrient-use efficiency, enhance soil biological activity, reduce dependence on synthetic fertilizers and pesticides, and increase crop resilience to biotic and abiotic stresses. Consequently, PGPR are increasingly utilized as biofertilizers and biostimulants to improve crop productivity while minimizing environmental impacts. Some of the most extensively studied PGPR genera include ***Azotobacter*, *Azospirillum*, *Bacillus*, *Pseudomonas*, *Rhizobium*, *Burkholderia*, *Enterobacter***, and ***Serratia***.

Mechanisms of Plant Growth Promotion

Direct Mechanisms: PGPR directly stimulate plant growth by increasing the availability and uptake of essential nutrients. They fix atmospheric nitrogen into plant-available forms, solubilize insoluble phosphorus, mobilize potassium, and enhance the availability of micronutrients such as zinc and iron through siderophore production. In addition, PGPR synthesize phytohormones including **indole-3-acetic acid (IAA)**, **gibberellins**, **cytokinins**, and **abscisic acid**, which promote cell division, root elongation, and overall plant development. These hormones stimulate root proliferation, increase root branching, improve nutrient absorption, and enhance water uptake, enabling plants to utilize soil resources more efficiently.

Indirect Mechanisms: PGPR also protect plants by suppressing pathogens and enhancing stress tolerance. They produce **ACC deaminase**, which lowers stress-induced ethylene levels, thereby improving plant tolerance to drought, salinity, and other environmental stresses. Furthermore, PGPR synthesize antibiotics, hydrogen cyanide, and lytic enzymes that inhibit soil-borne pathogens. They compete with harmful microorganisms for nutrients and ecological niches, form protective biofilms around roots, and activate **induced systemic resistance (ISR)**, strengthening the plant's natural defense system against diseases. Together, these mechanisms promote healthy plant growth while reducing reliance on chemical fertilizers and pesticides.

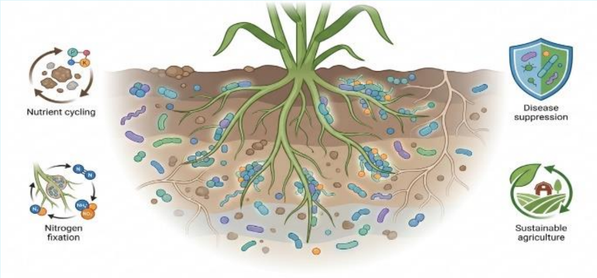

Figure1: Rhizosphere Interactions Mediated by Plant Growth-Promoting Rhizobacteria

Agricultural significance of PGPR's

1. Improvement of Soil Physical Properties: PGPR enhance soil structure by producing extracellular polymeric substances (EPS) and forming biofilms that bind soil particles into stable aggregates.

- Improve soil aggregation and aggregate stability
- Enhance soil structure and tilth
- Increase soil porosity and aeration
- Improve water infiltration and hydraulic conductivity
- Increase soil water-holding capacity
- Reduce soil bulk density
- Minimize soil erosion and surface crusting
- Promote deeper root penetration and root proliferation
- Improve soil resilience under drought conditions

2. Improvement of Soil Chemical Properties: PGPR improve soil fertility by increasing nutrient availability and regulating soil chemical processes.

- Fix atmospheric nitrogen (N_2)
- Solubilize insoluble phosphorus
- Mobilize potassium and micronutrients (Zn, Fe)
- Increase nutrient-use efficiency
- Enhance soil organic carbon accumulation
- Improve cation exchange capacity (CEC)
- Produce organic acids that regulate rhizosphere pH
- Reduce nutrient losses through leaching and volatilization
- Immobilize and detoxify heavy metals
- Improve long-term soil fertility

3. Improvement of Soil Biological Properties: PGPR stimulate beneficial microbial communities and enhance soil biological functioning.

- Increase microbial biomass carbon
- Enhance microbial diversity
- Improve rhizosphere biodiversity
- Stimulate beneficial fungi and bacteria
- Increase soil enzyme activities (dehydrogenase, phosphatase, urease)
- Accelerate decomposition of organic residues
- Enhance nutrient cycling
- Suppress soil-borne pathogens
- Improve soil ecosystem stability
- Strengthen soil resilience against environmental stresses.

4. Enhancement of Crop Productivity: PGPR promote plant growth through multiple direct and indirect mechanisms, resulting in sustainable yield improvement.

Growth Promotion

- Improve seed germination
- Enhance seedling vigor
- Stimulate root growth and branching
- Increase shoot biomass
- Improve nutrient uptake
- Enhance chlorophyll content and photosynthesis
- Increase flowering and fruit set
- Improve grain quality and nutritional value
- Increase crop yield and biomass production

Stress Tolerance

- Improve drought tolerance
- Enhance salinity tolerance
- Reduce heat and cold stress
- Increase tolerance to heavy metal toxicity
- Suppress fungal, bacterial, and nematode diseases
- Induce systemic resistance (ISR)

Sustainability Benefits

- Reduce chemical fertilizer requirement
- Lower pesticide application
- Reduce greenhouse gas emissions
- Improve fertilizer-use efficiency
- Promote climate-smart and regenerative agriculture

Table 1: Plant growth-promoting rhizobacteria and their reported effects on different crops

PGPR species	Crop	Major reported effect
Azospirillum brasilense	Maize (**Zea mays**)	Enhanced root growth, nitrogen uptake, grain yield and drought tolerance
Pseudomonas fluorescens	Wheat (**Triticum aestivum**)	Increased grain yield, phosphorus uptake, disease

		suppression and root biomass
Bacillus subtilis	Rice (**Oryza sativa**)	Improved nutrient uptake, plant height, chlorophyll content and yield
Bacillus amyloliquefaciens	Tomato (**Solanum lycopersicum**)	Increased fruit yield, nutrient uptake and resistance to soil-borne pathogens
Azotobacter chroococcum	Wheat	Improved nitrogen fixation, seed germination and grain yield
Paenibacillus polymyxa	Maize	Enhanced phosphorus solubilization, root development and biomass production
Pseudomonas putida	Chickpea (**Cicer arietinum**)	Improved phosphorus uptake, nodulation and plant biomass
Bacillus megaterium	Sunflower (**Helianthus annuus**)	Increased phosphorus availability,

		plant growth and seed yield
Azospirillum lipoferum	Maize	Enhanced root biomass, water-use efficiency and productivity under drought
Pseudomonas putida	Soybean (**Glycine max**)	Improved salt tolerance, nutrient uptake and biomass through phytohormone production

CONCLUSION

Plant Growth-Promoting Rhizobacteria offer an eco-friendly and sustainable approach to improving soil health and crop productivity. By enhancing nutrient availability, strengthening soil physical, chemical, and biological properties, and increasing plant resilience to environmental stresses, PGPR reduce dependence on agrochemicals and support climate-smart, resilient, and sustainable agricultural systems for future food security.