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Plant Growth-Promoting Rhizobacteria: Mechanisms, Ecological Significance and Agricultural Applications

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Plant growth-promoting rhizobacteria (PGPR) represent an ecologically sustainable alternative to chemical fertilizers and pesticides, offering improved plant nutrition, induced systemic resistance and enhanced resilience to biotic and abiotic stresses. These rhizosphere-associated bacteria promote plant growth through multiple mechanisms, including nitrogen fixation, phosphate solubilization, siderophore production, phytohormone synthesis, ACC deaminase activity and antagonism against pathogens. Rapid advancements in molecular biology, metagenomics and bioformulation technologies have expanded PGPR research, yet inconsistent field performance, regulatory barriers and limited commercialization remain key challenges. The study highlights the mechanisms governing PGPR-mediated plant growth promotion, evaluates their ecological significance in soil-plant-microbe interactions and discusses agricultural applications, constraints and future research directions to advance PGPR-based sustainable farming systems globally.

Keywords: PGPR, rhizosphere, biofertilizers, biocontrol, soil microbiome, induced systemic resistance (ISR), sustainable agriculture.

Introduction

Increasing global food demand, declining soil fertility and excessive dependency on chemical inputs challenge agricultural sustainability. Conventional fertilizers enhance yield but degrade soil structure, foster nutrient imbalance and contribute to greenhouse emissions (Tilman, 2011). In this context, plant growth-promoting rhizobacteria (PGPR) naturally occurring soil bacteria that colonize plant roots and enhance growth have emerged as promising bioinoculants for agroecological intensification. First described by Kloepper and Schroth in 1978, PGPR encompass diverse genera, including *Pseudomonas*, *Bacillus*, *Azotobacter*, *Azospirillum*, *Rhizobium*, *Burkholderia*, *Enterobacter and Streptomyces*, widely distributed across agricultural soils. PGPR enhance crop productivity through direct mechanisms (nutrient acquisition, hormone production) and indirect mechanisms (pathogen suppression, ISR), making them crucial for climate-resilient and resource-efficient agriculture.

Mechanisms of Plant Growth Promotion

Biological Nitrogen Fixation: Nitrogen-fixing PGPR convert atmospheric N_2 into plant-available ammonium through nitrogenase enzymes. Symbiotic rhizobia in legumes (e.g., *Rhizobium leguminosarum*, *Mesorhizobium ciceri*) form root nodules and contribute 40-350 kg N ha^{-1} $year^{-1}$ (Peoples *et al.*, 2009). Free-living species such as *Azotobacter* and *Azospirillum* also enhance nitrogen availability in cereals and oilseeds. **Phosphate Solubilization and Mineralization:** Around 75-90% of soil phosphorus remains insoluble and unavailable to plants. Phosphate-solubilizing bacteria (PSB), including *Pseudomonas*,

Bacillus and *Burkholderia*, release organic acids gluconic and citric acids that solubilize inorganic phosphates, enhancing P uptake and root development (Rodríguez & Fraga, 1999).
Siderophore Production: PGPR secrete siderophores that chelate Fe^{3+}, making iron more accessible to plants while depriving soilborne pathogens of essential iron, thereby contributing to biocontrol (Neilands, 1995). **Phytohormone Biosynthesis:** IAA, gibberellins, cytokinins and ethylene-modulating enzymes regulate plant growth. IAA-producing ***Pseudomonas*** and ***Azospirillum*** stimulate root elongation and nutrient uptake (Spaepen *et al*., 2007). PGPR-derived ACC deaminase lowers plant ethylene levels, reducing stress-induced growth inhibition.
Biocontrol and Antagonism: Many PGPR exhibit antagonism against phytopathogens through:

- Production of antibiotics (phenazines, 2,4-DAPG)
- Lytic enzymes (chitinases, β-1,3-glucanases)
- Hydrogen cyanide (HCN)
- Competition for nutrients and niches

These mechanisms suppress pathogens such as *Fusarium*, *Rhizoctonia*, *Pythium* and *Sclerotinia*.
Induced Systemic Resistance (ISR): ISR activates plant defense pathways involving jasmonic acid and ethylene signalling, strengthening plant immunity without compromising growth (Pieterse, 2014).

Ecological Significance of PGPR

Rhizosphere Microbiome Interactions: PGPR shape rhizosphere microbial networks, improve nutrient cycling and enhance soil organic carbon sequestration, contributing to long-term soil health (Bashan *et al*., 2014).
Stress Tolerance and Climate Resilience: PGPR improve plant tolerance to:

- Drought through osmolyte accumulation
- Salinity *via* ion homeostasis
- Heavy metal detoxification through bio-chelation
- Heat and oxidative stress through antioxidant modulation

These traits are critical for climate-smart agriculture (Grover, 2011).
Reduced Environmental Footprint: Biofertilizer-based PGPR systems lower chemical fertilizer requirements by 25-50%, reducing eutrophication, soil toxicity and greenhouse emissions (Carmen, 2019).

Agricultural Applications of PGPR

Biofertilizers and Seed Inoculants: Commercial PGPR-based products (*Bio-NPK*, *Rhizo-plus*, *Azospirillum* inoculants) are increasingly adopted in legumes, cereals, vegetables and oilseeds, enhancing yield and nutrient-use efficiency.
Biocontrol Agents: PGPR strains such as *Pseudomonas fluorescens* and *Bacillus subtilis* are successfully used against soilborne diseases in chickpea, wheat, tomato and groundnut.
Integrated Nutrient and Disease Management: PGPR synergize with organic manures, mycorrhizae, botanicals and reduced chemical fertilizers, supporting integrated sustainable farming systems.
Bioformulation and Delivery Technologies: Innovations include:

- Nano-encapsulated PGPR
- Polymer-coated seeds
- Liquid formulations with long shelf life
- Microbial consortia for multi-functionality

Challenges and Limitations

Despite proven benefits, adoption remains limited due to:

- Inconsistent field performance

- Strain-soil-crop specificity
- Poor shelf life and survival in harsh environments
- Lack of regulatory standardization
- Inadequate farmer awareness and commercialization pathways (Malusa & Vassilev, 2014)

Future Prospects

Future research must focus on:

- Microbiome engineering for targeted crop improvement
- Genomic editing (e.g., CRISPR) for enhanced PGPR traits
- Ai and machine learning for strain selection and field prediction
- Climate-resilient PGPR consortia
- Harmonized global biofertilizer regulations
- Country-specific PGPR strain repositories and sequencing databases

Integrating PGPR into precision agriculture may redefine sustainable crop production globally.

Conclusion

PGPR offer a scientifically validated, eco-friendly and economically viable strategy for improving plant growth, soil health and agricultural sustainability. Their multifunctional roles from nutrient acquisition to disease suppression make them indispensable for transitioning toward reduced chemical dependency and climate-resilient farming. Strengthening research, policy frameworks and industry partnerships will accelerate PGPR commercialization and global adoption.

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