Plant Growth-Promoting Rhizobacteria (PGPR): Sustainable Agriculture to Rescue Vegetation from Biotic Stress – A Review

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Abstract
Modern agriculture faces increasing pressure from biotic stresses such as fungal, bacterial and viral diseases, nematodes and insect pests, which together cause substantial yield losses and threaten global food security. Over-reliance on synthetic pesticides has led to environmental pollution, resistance development in pathogens and pests, and negative impacts on non-target organisms and human health. Plant growth-promoting rhizobacteria (PGPR) have emerged as a promising, eco-friendly alternative or complement to chemical inputs. PGPR are root-associated bacteria that enhance plant growth and health through multiple direct and indirect mechanisms. Direct mechanisms include biological nitrogen fixation, solubilization of phosphorus and other nutrients, production of phytohormones, siderophores, volatile organic compounds and ACC deaminase. Indirect mechanisms involve antibiosis, competition for nutrients and niches, production of cell wall–degrading enzymes, and activation of plant defense responses such as induced systemic resistance (ISR) and induced systemic tolerance (IST). Recent studies demonstrate that PGPR can effectively mitigate biotic stress caused by fungi, bacteria, viruses, nematodes and insect herbivores in diverse crops, while also improving resilience to abiotic stress, thereby contributing to sustainable intensification of agriculture.

This review summarizes the diversity and mechanisms of PGPR, with special emphasis on their role in managing biotic stress and enhancing plant immunity. Formulation technologies, modes of application and integration of PGPR into sustainable crop protection strategies are discussed. Finally, the review highlights current challenges, regulatory and commercialization issues, and future perspectives for large-scale adoption of PGPR-based bioproducts in agriculture.

Keywords: Plant growth-promoting rhizobacteria, PGPR, biotic stress, induced systemic resistance, biofertilizer, biocontrol, sustainable agriculture

1. Introduction

Plants are continuously challenged by a wide range of biotic stress factors including pathogenic fungi, bacteria, viruses, nematodes and insect pests. These stresses interfere with normal metabolic processes, reduce photosynthetic efficiency, impair nutrient and water uptake and ultimately result in yield and quality losses. Global estimates suggest that pests and diseases can account for 20–40% yield loss in major crops, even under intensive management. Chemical control has been the primary strategy for managing these stresses; however, indiscriminate use of pesticides has led to environmental contamination, development of resistant pathogen and pest strains, and concerns regarding food safety.

At the same time, climate change is altering pest and disease dynamics, often intensifying outbreaks and expanding the geographical range of many pathogens. There is therefore a strong need for sustainable, biologically based approaches that can safeguard crop productivity, restore soil health and reduce dependence on synthetic agrochemicals.

Plant growth-promoting rhizobacteria (PGPR) represent a key component of this paradigm shift. PGPR colonize the rhizosphere, rhizoplane or even internal root tissues and beneficially influence plant growth, nutrient acquisition and stress tolerance. Since the original conceptualization of PGPR in the late 1970s, a large body of evidence has accumulated demonstrating their potential in biocontrol and plant defense priming.

Recent reviews highlight that PGPR can enhance plant resilience to both abiotic and biotic stresses, modulate plant immunity through ISR, and contribute significantly to sustainable crop production systems.

2. Concept and Diversity of PGPR

2.1 Definition and ecological niche

PGPR are a diverse group of bacteria that live in close association with plant roots and promote plant growth and health either directly or indirectly. They may be:

- **Rhizosphere bacteria**: residing in soil influenced by root exudates
- **Rhizoplane bacteria**: colonizing the root surface
- **Endophytic PGPR**: residing within root tissues and sometimes aerial parts

These bacteria are attracted to the root zone by exudates containing sugars, amino acids, organic acids and secondary metabolites, which shape a highly selective micro-environment and determine the composition of the rhizosphere microbiome.

2.2 Taxonomic groups
Several bacterial genera are commonly reported as PGPR, including:
- **Pseudomonas** spp. (e.g., *P. fluorescens*, *P. putida*)
- **Bacillus** spp. (e.g., *B. subtilis*, *B. amyloliquefaciens*)
- **Azospirillum**, **Azotobacter** and other diazotrophs
- **Rhizobium* / *Mesorhizobium* (beyond their classical symbiotic N-fixing role)
- **Enterobacter**, **Serratia**, **Paenibacillus**, **Burkholderia** and others

They differ in their colonization strategies, metabolite production and compatibility with hosts, and hence consortia of multiple strains are often more effective than single-strain inoculants.

3. Mechanisms of Plant Growth Promotion by PGPR
PGPR promote plant growth through **direct** and **indirect** mechanisms. In the context of biotic stress, both types are important because overall plant vigor and nutrient balance strongly influence susceptibility to pathogens and pests.

3.1 Direct mechanisms
3.1.1 Biological nitrogen fixation
Certain PGPR can fix atmospheric nitrogen non-symbiotically or in associative symbiosis with plant roots. *Azospirillum*, *Azotobacter* and some *Pseudomonas* and *Enterobacter* strains possess nitrogenase activity and contribute to the nitrogen pool in the rhizosphere, thereby improving plant nutrition and reducing fertilizer requirements.

3.1.2 Solubilization of phosphorus and other minerals
Many PGPR release organic acids, protons and phosphatases that solubilize otherwise unavailable forms of phosphorus (e.g., tricalcium phosphate, rock phosphate). Some also mobilize potassium, zinc and iron. Enhanced nutrient availability leads to robust root and shoot growth, which indirectly supports better tolerance to pathogen attack.

3.1.3 Production of phytohormones
PGPR synthesize plant hormones such as:
- **Indole-3-acetic acid (IAA)** – stimulates root elongation, lateral root formation and root hair development
- **Gibberellins** – promote stem elongation and seed germination
- **Cytokinins** – influence cell division and shoot growth

These hormonal effects increase root surface area and nutrient uptake efficiency, which are crucial for overcoming stress conditions.

3.1.4 ACC deaminase activity
Ethylene is a stress hormone that, at high levels, inhibits root growth and can exacerbate stress symptoms. ACC deaminase–producing PGPR degrade 1-aminocyclopropane-1-carboxylate (ACC), the precursor of ethylene, thereby lowering stress ethylene levels in plants. This mechanism improves root growth under biotic and abiotic stress and is a key trait in many commercial PGPR strains.

3.1.5 Siderophores and iron acquisition
PGPR secrete siderophores—high-affinity iron-chelating compounds—that solubilize and sequester Fe^{3+} from the soil. Plants can access siderophore-bound iron, while pathogens are deprived of this essential micronutrient. Siderophore production therefore supports plant nutrition and simultaneously contributes to biocontrol.

3.1.6 Volatile organic compounds (VOCs)
Certain PGPR emit VOCs such as 2,3-butanediol and acetoin, which can stimulate plant growth, alter root architecture, and prime systemic defense responses. VOCs can act across distances in the rhizosphere, influencing both plants and other microbes.

3.2 Indirect mechanisms
Indirect mechanisms mainly contribute to **biotic stress management** and involve antagonism towards pathogens as well as activation of plant immunity.

3.2.1 Antibiosis
Many PGPR produce antibiotics and secondary metabolites (e.g., phenazines, pyoluteorin, 2,4-diacetylphloroglucinol, lipopeptides like surfactin and iturin) that inhibit pathogenic fungi and bacteria in the rhizosphere. These antibiotics may disrupt cell walls, membranes or vital metabolic pathways in pathogens.

3.2.2 Competition for nutrients and niche exclusion
Rapid colonization of the root surface enables PGPR to occupy physical niches and utilize root exudates more efficiently than pathogens. This competitive exclusion suppresses the establishment and proliferation of harmful microbes.

3.2.3 Lytic enzymes

PGPR synthesize extracellular enzymes such as chitinases, β-1,3-glucanases, proteases and cellulases that degrade fungal cell walls and other structural components of pathogens, directly reducing pathogen biomass in the rhizosphere.

3.2.4 Induced systemic resistance (ISR)

ISR is a plant-wide, enhanced defensive state triggered by beneficial microbes, including many PGPR. ISR is phenotypically similar to systemic acquired resistance (SAR) but is typically independent of salicylic acid and instead primarily involves jasmonic acid (JA) and ethylene signaling pathways.

Key features of ISR include:

- Priming of defense genes and faster, stronger responses upon pathogen attack
- Increased deposition of callose and lignin at cell walls
- Accumulation of defensive enzymes (peroxidases, chitinases, polyphenol oxidases)
- Enhanced production of reactive oxygen species (ROS) and secondary metabolites

Lipopeptides, lipopolysaccharides, certain siderophores and VOCs produced by PGPR act as microbe-associated molecular patterns (MAMPs) that activate ISR.

3.2.5 Induced systemic tolerance (IST)

IST is a closely related concept where PGPR prime plants to better tolerate abiotic stresses such as drought, salinity or heavy metal toxicity. Although IST focuses on abiotic stress, the same priming network often contributes to resilience under combined biotic and abiotic challenges.

4. Role of PGPR in Management of Biotic Stress

4.1 Control of fungal and oomycete diseases

Fungal pathogens such as *Fusarium*, *Rhizoctonia*, *Pythium*, *Sclerotium* and *Alternaria* cause root rots, wilts, damping-off and foliar diseases in numerous crops. PGPR-mediated suppression of these pathogens is one of the most widely documented benefits of PGPR.

Mechanisms involved include:

- Antibiotic production (e.g., 2,4-diacetylphloroglucinol, phenazines)
- Siderophore-mediated iron competition
- Lytic enzyme secretion
- ISR-mediated strengthening of plant cell walls and defense pathways

Field and greenhouse experiments have shown that seed treatment or soil application of *Pseudomonas fluorescens*, *Bacillus subtilis*, *B. amyloliquefaciens* and *Trichoderma*–PGPR consortia can significantly reduce disease incidence of Fusarium wilt in tomato, chickpea and banana, damping-off in vegetables and sheath blight in rice.

4.2 Suppression of bacterial diseases

Several PGPR strains exhibit antagonistic activity against bacterial pathogens such as *Xanthomona s*, *Ralstonia*, *Pectobacterium* and *Pseudomonas syringae*. Mechanisms include:

- Production of bacteriocins and antibiotics
- Competition for iron and nutrients
- ISR-mediated strengthening of plant defenses (e.g., enhanced oxidative burst and expression of pathogenesis-related proteins)

In crops like tomato, pepper and potato, PGPR-based formulations have shown promise in lowering the incidence of bacterial wilt and soft rot, particularly when used as part of integrated disease management strategies.

4.3 Alleviation of viral diseases

Although viruses cannot be directly attacked by PGPR, several studies demonstrate that ISR induced by rhizobacteria can reduce symptom severity and viral load. PGPR-treated plants often show enhanced levels of defense-related enzymes, phenolic compounds and PR proteins, which can limit virus replication and movement.

For example, PGPR inoculation has been reported to mitigate the effects of cucumber mosaic virus, tobacco mosaic virus and tomato yellow leaf curl virus in various host plants by priming their innate immune system.

4.4 Management of nematodes

Plant-parasitic nematodes such as *Meloidogyne* spp. (root-knot nematodes) and *Heterodera* spp. (cyst nematodes) cause significant damage to roots, leading to stunted growth and yield loss. Certain PGPR secrete nematicidal metabolites or enzymes, or they can induce systemic resistance that decreases nematode penetration and gall formation.

Moreover, improved root vigor and altered root exudation in PGPR-treated plants may make the rhizosphere less favorable for nematode infection. Combined application of PGPR with organic amendments or arbuscular mycorrhizal fungi (AMF) has shown synergistic effects in nematode management.

4.5 Effects on insect pests

PGPR can affect insect herbivores indirectly via ISR, leading to enhanced production of anti-herbivore compounds such as proteinase inhibitors, phenolics and alkaloids. Additionally, changes in plant volatile emissions induced by PGPR can alter insect behavior, sometimes attracting natural enemies (parasitoids, predators) of pests.

For instance, rhizobacteria-induced systemic resistance has been associated with reduced feeding and oviposition of aphids, whiteflies and caterpillars on treated plants, thereby lowering pest populations without direct insecticidal action.

5. Formulation, Delivery and Integration of PGPR in Sustainable Agriculture

5.1 Formulation technologies

To be commercially viable, PGPR must be formulated in a manner that ensures shelf life, ease of application and survival under field conditions. Common formulation types include:

- **Liquid formulations** – using nutrient broth or polymer-based carriers; easy to apply as seed coating or through irrigation
- **Solid formulations** – peat, lignite, talc or vermiculite–based powders and granules
- **Encapsulated formulations** – alginate beads or other encapsulation matrices that protect cells from desiccation and UV radiation

Advanced formulations combine PGPR with other beneficial microbes (e.g., AMF, *Trichoderma*) or with organic amendments and micronutrients to create multi-functional products.

5.2 Modes of application

PGPR can be applied through several methods:

1. **Seed treatment / seed coating**
   - Cost-effective and requires small quantities of inoculant
   - Ensures early colonization of the rhizosphere
2. **Seedling dip / root inoculation**
   - Common in nursery crops, vegetables and horticultural plants
3. **Soil application / broadcasting / furrow placement**
   - Granules or powders mixed with compost or farmyard manure
   - Suitable for field crops
4. **Drip or fertigation systems**
   - Liquid PGPR formulations applied through irrigation systems
   - Enhances distribution and contact with roots
5. **Foliar spray** (for certain PGPR strains)
   - Primarily for ISR induction and phyllosphere colonization

5.3 Integration with other management practices

For maximum impact, PGPR should be integrated into broader crop management strategies:

- **Integrated Pest Management (IPM):** PGPR can serve as a biological component alongside resistant varieties, cultural practices, pheromone traps and judicious pesticide use.
- **Organic and low-input farming:** PGPR-based biofertilizers and biopesticides are compatible with organic standards and can reduce reliance on external inputs.
- **Conservation agriculture:** Residue retention, reduced tillage and diversified rotations favor stable rhizosphere microbial communities, enhancing PGPR survival and activity.

6. Challenges and Future Prospects

Despite strong experimental evidence, the widespread adoption of PGPR technology faces several challenges:

6.1 Inconsistency of field performance

PGPR performance can vary across locations, seasons and cropping systems due to differences in soil type, native microbiota, climate and agronomic practices. Strains that perform well under controlled conditions may show reduced efficacy in farmers' fields.

Future direction:

- Selection of robust, stress-tolerant strains
- Use of multi-strain consortia to exploit complementary traits
- Tailor-made formulations for specific crops and regions

6.2 Survival and rhizosphere competence

For successful colonization, PGPR must survive storage, transport and harsh field conditions, then compete with native microbes in the rhizosphere.

Future direction:
- Improved carriers and protective additives in formulations
- Understanding quorum sensing and colonization traits at the molecular level
- Use of omics tools (metagenomics, transcriptomics) to monitor PGPR behavior in situ

6.3 Regulatory and quality control issues
PGPR products fall under biofertilizer or biopesticide regulations, which vary by country. Inadequate quality control can lead to products with low viable cell counts or contamination, undermining farmer confidence.

Future direction:
- Harmonized guidelines for registration and quality standards
- Certification systems for reliable PGPR products

6.4 Understanding plant–microbe–microbiome interactions
PGPR do not act alone; their effects are influenced by complex interactions within the plant holobiont and soil microbiome. More knowledge is needed on:
- Crosstalk between PGPR and other beneficial microbes (e.g., mycorrhizae, endophytes)
- Signaling networks linking ISR/IST with plant hormone pathways
- Plant genotype-specific responses to PGPR inoculation

6.5 Integration with modern breeding and biotechnology
There is growing interest in selecting crop varieties that are more responsive to beneficial microbes or that can recruit protective PGPR under stress conditions. PGPR-compatible genotypes and microbial traits could be combined for optimized plant–microbe partnerships.

7. Conclusion
Plant growth-promoting rhizobacteria offer a powerful, nature-based solution to mitigate the impact of biotic stresses on crops while simultaneously enhancing nutrient use efficiency and resilience to abiotic stress. Through a combination of direct and indirect mechanisms—including nutrient mobilization, hormone production, antibiosis, siderophore production, lytic enzyme activity and induction of systemic resistance—PGPR can reduce the incidence and severity of pathogens, nematodes and insect pests in a wide range of crops.

To fully realize their potential in sustainable agriculture, efforts must focus on developing robust, high-quality PGPR formulations adapted to local conditions, integrating them into IPM and conservation agriculture frameworks, and strengthening regulatory and quality control systems. Advances in molecular biology, genomics and microbiome research will accelerate the discovery of novel PGPR strains and unravel the complex signaling networks involved in plant immunity and stress tolerance.

Given the escalating challenges of climate change, pesticide resistance and environmental degradation, PGPR-based technologies are poised to play a central role in developing resilient, resource-efficient and environmentally sound agricultural systems.

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