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Plant growth-promoting rhizobacteria as sustainable bio-inputs for modern agriculture: A critical review

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Abstract
These beneficial rhizospheric microorganisms enhance plant growth through multiple direct and indirect mechanisms, including biological nitrogen fixation, phosphate solubilization, phytohormone production, siderophore release, and suppression of plant pathogens. In the context of modern agriculture, where sustainability, climate resilience, and resource-use efficiency are critical, PGPR offer eco-friendly alternatives to conventional agro-inputs. This review critically examines recent advances in PGPR research, focusing on their functional mechanisms, role in nutrient acquisition, stress tolerance enhancement, and disease management. Special emphasis is given to their performance under abiotic stresses such as drought, salinity, and heavy metal contamination, which are increasingly prevalent under changing climatic conditions. Furthermore, challenges associated with PGPR commercialization, field-level consistency, formulation stability, and regulatory constraints are discussed. Emerging trends, including omics-based PGPR characterization, microbiome engineering, and integration with precision agriculture technologies, are also highlighted. The review concludes by identifying key research gaps and future prospects for large-scale adoption of PGPR as sustainable bio-inputs in modern agricultural systems. Overall, PGPR represent a vital component of next-generation sustainable agriculture, contributing to improved crop productivity, soil health, and environmental sustainability.

Keywords: Plant growth-promoting rhizobacteria, sustainable agriculture, biofertilizers, rhizosphere microorganisms, soil health, abiotic stress tolerance, biotic stress management

1. Introduction
Modern agriculture faces the dual challenge of achieving higher crop productivity to meet the ever-growing global food demand while significantly minimizing environmental degradation caused by the intensive use of chemical fertilizers and pesticides. The indiscriminate application of synthetic agrochemicals has been linked to soil fertility decline, nutrient imbalance, groundwater contamination, biodiversity loss, and increased greenhouse gas emissions, prompting a shift toward sustainable alternatives (Gupta *et al*., 2023) [9].

Plant Growth-Promoting Rhizobacteria (PGPR), a group of beneficial rhizospheric bacteria, have emerged as key bio-inputs capable of enhancing plant growth through multiple biological mechanisms while reducing reliance on synthetic inputs. These microorganisms colonize the rhizosphere—the dynamic soil zone surrounding plant roots—and enhance plant development through direct nutrient acquisition and indirect defense modulation (Hasan *et al*., 2024; Mohanty *et al*., 2021; Etesamy *et al*., 2020; Basu *et al*., 2021) [12, 22, 2].

PGPR promote plant growth directly by fixing atmospheric nitrogen, solubilizing insoluble phosphates, mobilizing micronutrients, and synthesizing phytohormones like indole-3-acetic acid, gibberellins, and cytokinins, which regulate growth and development (Shetty *et al*., 2025) [30]. Indirect mechanisms include siderophore production, antibiosis, secretion of lytic enzymes, and induction of systemic resistance (ISR) in host plants, which collectively suppress phytopathogens and improve resilience (Yang *et al*., 2024) [34].

In the context of contemporary challenges such as drought, salinity, and other abiotic stresses exacerbated by climate change, PGPR have shown promising potential to improve plant stress tolerance by modulating physiological and biochemical pathways (Sahu *et al*., 2025) [29]. Their ability to enhance water-use efficiency, nutrient uptake, and stress adaptation underscores the relevance of PGPR in climate-smart and sustainable agricultural systems.

Despite these advantages, large-scale adoption of PGPR-based bio-inputs faces several obstacles, including inconsistent field performance, formulation instability, limited shelf life, and complex interactions with soil, crop genotype, and local environmental factors. Furthermore, gaps remain in translating laboratory and greenhouse successes to reliable field applications.

In this context, the present review critically examines the role of plant growth-promoting rhizobacteria as sustainable bio-inputs for modern agriculture. Emphasis is placed on elucidating their multifaceted mechanisms, applications in nutrient management and stress mitigation, commercialization challenges, and emerging research trends. By synthesizing recent advances and identifying key knowledge gaps, this review aims to provide a comprehensive perspective on the potential of PGPR in advancing sustainable and resilient agricultural production systems.

2. Concept and classification of plant growth-promoting rhizobacteria (PGPR)

Plant Growth-Promoting Rhizobacteria (PGPR) are a diverse group of beneficial soil microorganisms that colonize the rhizosphere and exert positive effects on plant growth, development, and health. The term PGPR was first introduced to describe root-associated bacteria capable of enhancing crop productivity through direct and indirect biological mechanisms. In recent years, PGPR have gained renewed attention due to their potential to function as sustainable bio-inputs that reduce dependence on synthetic fertilizers and pesticides (Gupta *et al*., 2023; Hasan *et al*., 2024) [9, 12].

The rhizosphere represents a highly dynamic and biologically active zone influenced by root exudates, microbial interactions, and soil physicochemical properties. PGPR successfully colonize this niche by utilizing root-derived carbon sources and establishing beneficial associations with plants. These interactions may range from loose, free-living associations to tightly regulated symbiotic and endophytic relationships (Yang *et al*., 2024) [34]. Recent studies emphasize that effective rhizosphere competence and persistence are key determinants of PGPR efficacy under field conditions (Mano *et al*., 2025) [20].

2.1 Classification Based on Ecological Association

Based on their mode of association with plant roots, PGPR are broadly classified into three major groups:

Free-living PGPR reside in the rhizosphere soil and influence plant growth without forming intimate associations with plant tissues. Genera such as *Azotobacter*, *Bacillus*, and *Pseudomonas* fall under this category and are well known for nutrient solubilization and pathogen suppression (*Shetty et al., 2025*) [30].

Associative PGPR establish close interactions with plant roots, often forming biofilms on the root surface. These bacteria benefit from root exudates while enhancing nutrient uptake and hormonal balance in host plants. *Azospirillum* species are classical examples of associative PGPR widely studied in cereal crops (*Sahu et al., 2025*) [29].

Endophytic PGPR colonize internal plant tissues without causing harm and provide growth-promoting benefits from within the plant system. Endophytic PGPR are increasingly recognized for their role in stress tolerance and long-term plant protection due to their protected ecological niche (Mano *et al*., 2025; Yang *et al*., 2024) [20, 34].

2.2 Classification Based on Functional Attributes

PGPR can also be classified according to their dominant functional traits:

Biofertilizer PGPR, involved in biological nitrogen fixation, phosphate solubilization, and micronutrient mobilization

Bioprotectant PGPR, which suppress plant pathogens through antibiosis, siderophore production, and induced systemic resistance

Stress-ameliorating PGPR, capable of enhancing tolerance to drought, salinity, heavy metals, and temperature extremes

2.3 Major PGPR Genera of Agricultural Importance

Several bacterial genera have been extensively reported as effective PGPR across diverse cropping systems. These include *Bacillus*, *Pseudomonas*, *Rhizobium*, *Azospirillum*, *Enterobacter*, *Serratia*, and *Burkholderia*. Among these, *Bacillus* and *Pseudomonas* species are particularly favored for commercial formulations due to their spore-forming ability, shelf-life stability, and broad-spectrum activity (Gupta *et al*., 2023; Shetty *et al*., 2025) [9, 30].

Recent studies from tropical and subtropical agro-ecosystems indicate that indigenous PGPR strains often outperform introduced strains due to better adaptation to local soil and climatic conditions (*Mano et al., 2025*) [20]. This observation underscores the importance of location-specific PGPR selection for sustainable agricultural applications.

3. Mechanisms of plant growth promotion by PGPR

Plant Growth-Promoting Rhizobacteria (PGPR) enhance plant growth through direct and indirect mechanisms that collectively improve nutrient availability, stress tolerance, and crop health (*Yang et al., 2024*) [34]. These mechanisms reflect the multifaceted interaction between PGPR and host plants and are key to their potential as sustainable bio-inputs in modern agriculture.

3.1 Direct Mechanisms

3.1.1 Biological Nitrogen Fixation

Many PGPR can fix atmospheric nitrogen, converting inert N_2 into plant-usable forms such as ammonium. This process reduces reliance on synthetic nitrogen fertilizers, increases soil fertility, and enhances plant growth (Olanrewaju *et al., 2017*; *Hail et al., 2016*) [25, 13]. By improving nitrogen availability, PGPR contribute to higher biomass and yield.

3.1.2 Phosphate Solubilization and Nutrient Mobilization

Phosphorus is a critical macronutrient often present in insoluble forms in soil. PGPR secrete organic acids and phosphatases that solubilize bound phosphorus, making it available for root uptake (*Kundan et al., 2015*; *Bhandari et al., 2025; Tariq et al., 2022*) [17, 3, 32]. Additionally, PGPR can mobilize micronutrients like iron, zinc, and potassium, promoting balanced nutrient acquisition. *(Nazir et al., 2018*; *Han et al., 2006)* [24, 11].

3.1.3 Phytohormone Production

PGPR synthesize plant hormones including indole-3-acetic acid (IAA), gibberellins, and cytokinins, which regulate key developmental processes such as root elongation, cell division, and shoot growth (*Glick et al., 2012; Prakash et al., 2013*) [7, 26]. Enhanced root systems improve water and nutrient absorption under both normal and stress conditions (*Agarwal et al., 2013; Kesavardhini et al., 2025*) [, 15].

3.2 Indirect Mechanisms

3.2.1 Siderophore Production and Disease Suppression

PGPR produce siderophores—high-affinity iron chelators—that deprive pathogenic microbes of essential iron, leading to reduced disease incidence (*Gupta et al., 2023*; *Tian et al., 2009*) [9, 33]. These siderophores also facilitate iron uptake by plants, improving chlorophyll synthesis and photosynthesis (*Goswami al., 2016*; *Rezanka et al., 2018; Czarnes et al., 2020*) [8, 27, 5]

3.2.2 Induced Systemic Resistance (ISR)
PGPR can trigger plant immune responses, enhancing systemic resistance to pathogens. This ISR mechanism enables plants to defend more efficiently against a range of biotic stresses without chemical pesticides (*Solano et al., 2008; Yang et al., 2024*) [31, 34].

3.2.3 Abiotic Stress Amelioration
PGPR alleviate stress conditions such as drought, salinity, and heavy metal toxicity through multiple pathways, including increased antioxidant enzyme activities, ACC deaminase production, and osmolyte accumulation (*Liu et al., 2025*; *Kesavardhini et al., 2025*) [18, 15]. For example, PGPR-mediated modulation of ethylene levels via ACC deaminase reduces stress-induced growth inhibition.

3.2.4 Enzyme Production Against Pathogens
PGPR secretes enzymes such as chitinases and glucanases that degrade fungal cell walls, helping to suppress diseases like Fusarium root rot. Ex: *Pseudomonas and Bacillus sps (Gupta, et al., 2006)* [10].

3.3 Microbial Community Interactions and Synergetic Effects
Recent omics-based studies highlight that PGPR perform optimally in complex microbial consortia where synergistic interactions improve nutrient cycling and stress resistance (*Mmotla et al., 2025*) [21]. Such interactions underline the importance of microbial community dynamics in rhizosphere functioning.

4. Role of PGPR in nutrient use efficiency
Plant Growth-Promoting Rhizobacteria (PGPR) significantly enhance nutrient use efficiency (NUE) in crops by facilitating the acquisition, mobilization, and uptake of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients. These functions position PGPR as key sustainable bio-inputs that reduce dependency on synthetic fertilizers and improve soil fertility (*Yang et al., 2024*; *Bhandari et al., 2025*) [34, 3].

4.1 Nitrogen Fixation and Nitrogen Use Efficiency
Many PGPR possess the ability to fix atmospheric nitrogen (N_2) into plant-available ammonium (NH_4^+), which directly enhances nitrogen availability for crops. This biological nitrogen fixation is especially critical in cereal and legume systems where nitrogen demand is high. By reducing the need for chemical nitrogen fertilizers, PGPR can lower production costs and environmental pollution linked to fertilizer overuse (*Bhattacharyya et al., 2012; Yang et al., 2024*) [4, 34].

4.2 Phosphorus Solubilization and Mobilization
A major limiting factor in agricultural soils is the low availability of soluble phosphorus. PGPR enhance phosphorus availability by secreting organic acids, phosphatases, and other solubilizing agents that convert insoluble phosphorus compounds into forms that roots can absorb. Enhanced P availability improves root growth and plant vigor, thereby increasing phosphorus use efficiency (*Kumar et al., 2016; Rivas et al., 2006; Zhang et al., 2020*) [16, 28, 35].

4.3 Micronutrient Solubilization and Uptake
Besides N and P, PGPR also play roles in mobilizing micronutrients such as iron (Fe), zinc (Zn), and potassium (K). Siderophore-producing PGPR can chelate iron and improve its bioavailability, whereas other strains affect potassium and micronutrient solubilization, enhancing uptake and balancing plant nutrition (*Yang et al., 2024; Lopes et al., 2021; Kumran et al., 2017*) [34, 19,].

4.4 Improvement of Soil Structure and Water Retention
PGPR that produce exopolysaccharides (EPS) improve soil aggregation and water retention, creating a favorable environment for nutrient cycling and root proliferation. Better soil structure increases both nutrient and water use efficiency, especially under marginal soil conditions (*Bhandari et al., 2025*) [3].

4.5 Synergistic Interactions with Fertilizer Amendments
Recent research indicates that integrating PGPR with reduced fertilizer doses can lead to synergistic effects, improving both yield and nutrient efficiency. For example, combining PGPR with organic amendments or balanced fertilizer regimes boosted yield and nutrient uptake in canola and other crops (*Muhammad et al., 2025*) [23]. Overall, by enhancing nutrient availability and uptake, PGPR contribute to sustainable nutrient management, reduce environmental harm, and support climate-smart agriculture (*Yang et al., 2024*) [34].

Table 1: Role of PGPR's used in crop production:

Crop(s)	PGPR Traits Identified	Key Outcomes	Author(s)
Wheat, Rice	N_2 fixation, phosphate solubilization, siderophore production	Improved nutrient uptake, increased biomass, reduced chemical fertilizer requirement	*Gupta et al. 2023* [9]
Tomato, Maize	IAA production, ACC deaminase, ISR induction	Enhanced root architecture, improved stress tolerance, yield improvement	*Hasan et al., 2024* [12]
Multiple crops (review)	N fixation, P solubilization, biocontrol activity	Strengthened nutrient use efficiency and disease suppression	*Yang et al., 2024* [34]
Rice, Groundnut	ACC deaminase, antioxidant enzyme activation	Enhanced drought tolerance and physiological stability	*Kesavardhini et al., 2025* [15]
Vegetables, Cereals	Phosphate solubilization, EPS production	Improved soil aggregation, nutrient availability, and crop growth	*Bhandari et al., 2025* [3]
Canola (*Brassica napus*)	N fixation, P mobilization, synergistic fertilizer interaction	Increased yield and fertilizer use efficiency	*Muhammad et al., 2025* [23]
Horticultural crops	Phytohormone synthesis, micronutrient solubilization	Improved plant vigor, flowering, and yield quality	*Shetty et al., 2025* [30]
Multiple crops (omics review)	Multi-trait PGPR consortia, microbiome interaction	Enhanced rhizosphere stability and stress resilience	*Mmotla et al., 2025* [21]
Maize, Sorghum	IAA production, P solubilization, siderophore activity	Location-specific PGPR showed superior field performance and yield	*Mano et al., 2025* [20]
Flower crops	Endophytic colonization, hormone regulation	Increased flower yield, quality, and stress tolerance	*Sahu et al., 2025* [29]

5. PGPR in stress tolerance: abiotic and biotic stresses

Agricultural productivity is increasingly constrained by a range of abiotic and biotic stresses intensified by climate change, soil degradation, and intensive cropping systems. Drought, salinity, temperature extremes, nutrient deficiency, and plant diseases significantly reduce crop yield and stability. In this context, Plant Growth-Promoting Rhizobacteria (PGPR) have gained prominence as sustainable bio-inputs capable of enhancing plant tolerance to stress through physiological, biochemical, and molecular modulation (*Yang et al., 2024; Kesavardhini et al., 2025*) [34, 15].

5.1 PGPR-Mediated Tolerance to Abiotic Stresses

5.1.1 Drought Stress

Drought stress adversely affects plant water relations, photosynthesis, and nutrient uptake. PGPR alleviate drought stress by improving root architecture, enhancing water-use efficiency, and regulating stress-responsive phytohormones. Many PGPR produce ACC deaminase, which lowers ethylene levels in plants, thereby preventing stress-induced growth inhibition (*Liu et al., 2025*) [18]. Additionally, PGPR enhance the accumulation of osmolytes such as proline and activate antioxidant enzymes, reducing oxidative damage under water-limited conditions (*Kesavardhini et al., 2025*) [15].

Field and greenhouse studies have demonstrated improved drought tolerance in crops such as rice, maize, wheat, and sorghum following inoculation with drought-adaptive PGPR strains (*Mano et al., 2025*) [20].

5.1.2 Salinity Stress

Soil salinity disrupts ion balance, causes osmotic stress, and impairs plant metabolism. PGPR mitigate salinity stress by regulating ion homeostasis, enhancing potassium uptake, and reducing sodium toxicity. Salinity-tolerant PGPR also induce antioxidant defense systems and promote hormonal balance, leading to improved growth under saline conditions (*Hasan et al., 2024; Shetty et al., 2025*) [12, 30].

5.1.3 Temperature Extremes and Heavy Metal Stress

Extreme temperatures and heavy metal contamination pose emerging threats to crop productivity. PGPR confer tolerance to heat and cold stress by stabilizing cellular membranes and enhancing stress-related gene expression. In metal-contaminated soils, PGPR immobilize or detoxify heavy metals through biosorption, chelation, and enzymatic transformation, thereby reducing metal uptake by plants (*Bhandari et al., 2025; Yang et al., 2024*) [3, 34].

5.2 PGPR-Mediated Tolerance to Biotic Stresses

5.2.1 Disease Suppression and Biocontrol

PGPR play a crucial role in suppressing plant pathogens through multiple antagonistic mechanisms. These include siderophore production, antibiosis, competition for nutrients and niches, and secretion of cell wall-degrading enzymes such as chitinases and glucanases (*Gupta et al., 2023*) [9]. Such mechanisms reduce pathogen proliferation in the rhizosphere and protect crops from soil-borne and foliar diseases.

5.2.2 Induced Systemic Resistance (ISR)

Beyond direct antagonism, PGPR can activate plant defense pathways through induced systemic resistance (ISR). ISR primes the plant immune system, enabling faster and stronger defense responses against subsequent pathogen attacks. Unlike chemical pesticides, ISR does not impose selection pressure on pathogens and is environmentally benign (*Yang et al., 2024*) [34].

Recent studies indicate that ISR-inducing PGPR are effective against a broad spectrum of pathogens, including fungi, bacteria, and nematodes, making them valuable components of integrated disease management strategies (*Sahu et al., 2025*) [29].

5.3 Integrated Stress Management Using PGPR

The multifunctional nature of PGPR enables them to simultaneously mitigate abiotic and biotic stresses, offering an integrated stress management approach. Recent advances highlight the superiority of multi-trait PGPR consortia over single-strain inoculants, particularly under field conditions where multiple stresses coexist (*Mmotla et al., 2025*) [21]. Indigenous and crop-specific PGPR strains have shown enhanced adaptability and consistent performance across diverse agro-climatic zones (*Mano et al., 2025*) [20].

5.4 Critical Assessment and Research Gaps

Despite extensive evidence of PGPR-mediated stress tolerance, variability in field performance remains a major challenge. Soil type, climatic conditions, crop genotype, and microbial competition influence PGPR efficacy. Furthermore, long-term impacts of repeated PGPR application on native soil microbial communities require further investigation.

Overall, PGPR represent a promising, eco-friendly strategy for enhancing crop resilience against abiotic and biotic stresses. Their ability to modulate plant physiology, improve soil health, and suppress pathogens underscores their importance as sustainable bio-inputs in modern agriculture.

6. PGPR as Sustainable Bio-Inputs in Modern Agriculture

The concept of sustainable agriculture emphasizes the efficient use of natural resources, environmental protection, and long-term productivity. In this context, Plant Growth-Promoting Rhizobacteria (PGPR) have emerged as promising **sustainable bio-inputs** that complement or partially replace chemical fertilizers and pesticides. Their multifunctional nature allows them to enhance crop productivity while maintaining soil health and ecological balance (*Yang et al., 2024; Hasan et al., 2024*) [34, 12].

6.1 PGPR as Biofertilizers

PGPR-based biofertilizers improve crop nutrition through biological nitrogen fixation, phosphate solubilization, potassium mobilization, and micronutrient chelation. Unlike synthetic fertilizers, these bio-inputs operate through natural biological processes and contribute to gradual improvement in soil fertility (*Gupta et al., 2023*) [9]. Several studies have demonstrated that integrating PGPR with reduced fertilizer doses maintains or enhances crop yield while lowering input costs and environmental risks (*Muhammad et al., 2025*) [23].

Spore-forming PGPR such as *Bacillus* spp. and metabolically versatile genera like *Pseudomonas* are widely used in commercial biofertilizer formulations due to their shelf stability and broad-spectrum activity (*Shetty et al., 2025*) [30].

6.2 PGPR as Biopesticides and Biocontrol Agents

PGPR also function as effective biopesticides by suppressing plant pathogens through antagonistic mechanisms such as antibiosis, siderophore production, competition for nutrients, and induction of systemic resistance (ISR). Unlike chemical pesticides, PGPR-based biocontrol agents are target-specific, biodegradable, and pose minimal risk to non-target organisms (*Gupta et al., 2023; Yang et al., 2024*) [9, 34].

Their integration into Integrated Pest and Disease Management (IPDM) systems has shown significant potential in reducing chemical pesticide use while maintaining effective disease control in cereals, vegetables, and horticultural crops (*Sahu et al., 2025*) [29].

6.3 Role of PGPR in Climate-Smart Agriculture
Climate-smart agriculture aims to enhance productivity, adaptation, and mitigation under changing climatic conditions. PGPR contribute to climate resilience by improving stress tolerance, water-use efficiency, and nutrient cycling. Their ability to mitigate drought, salinity, and temperature stress makes them valuable tools in climate-vulnerable agro-ecosystems (*Kesavardhini et al., 2025; Liu et al., 2025*) [15, 18].
Recent research emphasizes the importance of selecting stress-adapted and indigenous PGPR strains, which show better survival and performance under local soil and climatic conditions (*Mano et al., 2025*) [20].

6.4 Integration with Organic, Natural, and Precision Farming Systems
PGPR are highly compatible with organic and natural farming systems, where synthetic inputs are restricted. Their use supports soil biological activity, nutrient recycling, and ecological sustainability (*Bhandari et al., 2025*) [3]. Moreover, emerging precision agriculture approaches integrate PGPR application with site-specific nutrient and water management, enhancing overall input-use efficiency (*Yang et al., 2024*) [34].
Advances in microbial formulations, carrier materials, and seed-coating technologies have further improved the applicability of PGPR in modern farming systems.

6.5 Multifunctional PGPR Consortia
Recent studies indicate that PGPR consortia, comprising multiple strains with complementary traits, outperform single-strain inoculants under field conditions. Such consortia enhance nutrient availability, stress tolerance, and disease resistance simultaneously, offering a holistic solution for sustainable crop production (*Mmotla et al., 2025; Mano et al., 2025*) [21, 20].

6.6 Critical Perspective
Despite their advantages, the effectiveness of PGPR as bio-inputs depends on formulation quality, strain compatibility, crop specificity, and environmental factors. Standardization of bio-input quality, farmer awareness, and supportive policy frameworks remain crucial for large-scale adoption.
Overall, PGPR represent a cornerstone of sustainable bio-input strategies in modern agriculture. Their multifunctional roles as biofertilizers, biopesticides, and stress mitigators position them as key components of climate-smart, resource-efficient, and environmentally responsible farming systems.

7. Commercialization challenges and field-level constraints of PGPR
Despite extensive research demonstrating the growth-promoting and stress-mitigating potential of Plant Growth-Promoting Rhizobacteria (PGPR), their large-scale commercialization and consistent field performance remain challenging. The transition of PGPR from laboratory and greenhouse studies to reliable field applications is influenced by multiple biological, environmental, technical, and socio-economic factors (*Yang et al., 2024; Bhandari et al., 2025*) [34, 3].

7.1 Inconsistent Field Performance
One of the major limitations in PGPR commercialization is the variability in field efficacy PGPR strains that perform well under controlled conditions often show inconsistent results in open-field environments due to complex interactions among soil properties, climate, crop genotype, and native microbial communities (*Hasan et al., 2024*) [12]. Soil pH, moisture, organic matter content, and temperature significantly influence PGPR survival and colonization efficiency (*Mano et al., 2025*) [20].

7.2 Rhizosphere Competence and Survival
Successful PGPR application depends on the ability of the inoculated strains to compete with indigenous soil microflora and establish a stable population in the rhizosphere. Many introduced PGPR fail to persist due to poor adaptability or lack of rhizosphere competence, resulting in reduced effectiveness (*Mmotla et al., 2025*) [21]. This challenge highlights the importance of selecting indigenous and crop-specific PGPR strains for commercial use (*Mano et al., 2025*) [20].

7.3 Formulation, Shelf Life, and Carrier Constraints
PGPR formulations face technical challenges related to short shelf life, sensitivity to temperature, and loss of viability during storage and transportation. Liquid and carrier-based formulations often show reduced microbial counts over time, affecting product quality and performance. Although spore-forming bacteria such as *Bacillus* spp. exhibit better shelf stability, many effective PGPR strains lack such resilience (*Shetty et al., 2025*) [30].
Advances in carrier materials, encapsulation techniques, and nano-formulations have shown promise in improving shelf life and delivery efficiency, but their large-scale adoption remains limited (*Bhandari et al., 2025*) [3].

7.4 Standardization, Quality Control, and Regulatory Issues
Lack of uniform quality standards and regulatory frameworks poses another significant challenge to PGPR commercialization. Variations in microbial count, strain identity, and contamination levels among commercial products reduce farmer confidence and adoption (*Gupta et al., 2023*) [9]. In many developing countries, bio-input regulations are still evolving, leading to inconsistent quality assurance mechanisms.

7.5 Farmer Awareness and Adoption Barriers
Limited awareness among farmers regarding the correct application methods, timing, and benefits of PGPR-based products restricts their adoption. Additionally, delayed or inconsistent yield responses compared to chemical inputs discourage farmers from switching to bio-inputs (*Sahu et al., 2025*) [29]. Strengthening extension services and demonstrating long-term benefits through on-farm trials are essential for wider acceptance.

7.6 Economic and Market Constraints
The commercialization of PGPR also faces economic challenges such as high production costs, limited market penetration, and competition with subsidized chemical fertilizers. The absence of immediate economic returns often hampers investment in microbial bio-inputs (*Yang et al., 2024*) [34].

7.7 Critical Outlook
Addressing commercialization challenges requires a

multidisciplinary approach, integrating microbiology, agronomy, formulation science, policy support, and farmer education. Long-term field validation, strain standardization, and supportive regulatory policies are essential for successful PGPR-based bio-input deployment.

While PGPR hold immense promise as sustainable bio-inputs, overcoming challenges related to field performance, formulation stability, quality control, and adoption is critical for their successful commercialization and large-scale use in modern agriculture.

8. Emerging trends and advanced approaches in pgpr research

With advancements in molecular biology, data analytics, and agricultural technologies, research on Plant Growth-Promoting Rhizobacteria (PGPR) has evolved beyond traditional culture-based studies. Emerging approaches now focus on understanding PGPR at the genomic, systems, and ecosystem levels, enabling more precise, effective, and scalable applications in modern agriculture (*Yang et al., 2024; Mmotla et al., 2025*) [34, 21].

8.1 Omics-Based Characterization of PGPR

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, have significantly enhanced the understanding of PGPR functional traits and plant-microbe interactions. Whole-genome sequencing enables the identification of genes responsible for nitrogen fixation, phytohormone synthesis, stress tolerance, and biocontrol activity. Such insights facilitate the selection of elite PGPR strains with multifunctional capabilities (*Mmotla et al., 2025*) [21].

Metagenomic approaches have further revealed the complexity of rhizosphere microbial communities and their collective influence on plant health. These techniques support the development of microbiome-informed PGPR consortia rather than single-strain inoculants (*Yang et al., 2024*) [34].

8.2 Microbiome Engineering and PGPR Consortia

Recent research emphasizes microbiome engineering, where beneficial microbial communities are intentionally assembled to enhance plant performance. PGPR consortia comprising complementary strains improve nutrient cycling, stress tolerance, and disease resistance more effectively than individual strains (*Mano et al., 2025*) [20].

Microbiome manipulation strategies include selective enrichment of native PGPR, co-inoculation with mycorrhizae, and rhizosphere conditioning using organic amendments. These approaches promote long-term stability and resilience of beneficial microbial populations (*Bhandari et al., 2025*) [3].

8.3 Artificial Intelligence and Data-Driven PGPR Selection

Artificial intelligence (AI) and machine learning tools are increasingly applied to predict PGPR performance under diverse agro-climatic conditions. AI-based models integrate soil properties, climate data, crop genotype, and microbial traits to optimize PGPR strain selection and application strategies (*Yang et al., 2024*) [34].

Such decision-support systems enhance precision agriculture by enabling site-specific microbial interventions, reducing trial-and-error approaches and improving adoption success rates.

8.4 Advanced Formulation and Delivery Technologies

Innovations in formulation science aim to overcome shelf-life and delivery challenges associated with PGPR commercialization. Techniques such as microencapsulation, nano-carriers, polymer-based coatings, and seed priming technologies enhance microbial survival, targeted delivery, and field efficacy (*Shetty et al., 2025*) [30].

These advanced formulations protect PGPR from environmental stress during storage and application, ensuring better rhizosphere colonization.

8.5 Integration with Precision and Digital Agriculture

PGPR applications are increasingly integrated with precision agriculture tools, including variable-rate application systems, remote sensing, and soil health monitoring platforms. This integration enables optimal timing and dosage of microbial bio-inputs, improving resource-use efficiency and crop productivity (*Yang et al., 2024*) [34].

8.6 Biosafety, Risk Assessment, and Regulatory Innovations

Emerging research also addresses biosafety concerns related to large-scale PGPR use. Genome-based screening for pathogenicity, antibiotic resistance, and environmental persistence supports the safe deployment of PGPR-based products (*Mmotla et al., 2025*) [21]. Regulatory frameworks are gradually evolving to accommodate these scientific advancements.

Emerging omics-driven, AI-enabled, and formulation-based innovations are transforming PGPR research from empirical approaches to precision-oriented solutions. These advancements are expected to enhance the reliability, scalability, and impact of PGPR as sustainable bio-inputs in modern agriculture.

9. Future prospects and research gaps

Despite significant progress in understanding and utilizing Plant Growth-Promoting Rhizobacteria (PGPR), several research gaps and opportunities remain that must be addressed to enable their widespread adoption as sustainable bio-inputs in modern agriculture. One major gap lies in the translation of laboratory and greenhouse findings to consistent field performance. Long-term, multi-location field trials across diverse agro-climatic zones are essential to validate PGPR efficacy under real farming conditions.

Another critical area is the development of crop- and region-specific PGPR consortia. Indigenous PGPR strains adapted to local soil and climatic conditions often outperform introduced strains, yet their systematic identification and utilization remain limited (*Mano et al., 2025*) [20]. Future research should prioritize the exploration of native microbial diversity and its integration into customized bio-input formulations.

The mechanistic understanding at molecular and systems levels also requires further investigation. Although omics technologies have advanced PGPR research, linking genomic potential with actual field functionality remains a challenge. Integrative studies combining genomics, transcriptomics, metabolomics, and phenotyping are needed to predict PGPR performance more accurately (*Mmotla et al., 2025*) [21].

From a technological perspective, improvements in formulation stability, shelf life, and delivery systems are necessary to enhance product reliability. Research on novel carriers, encapsulation techniques, and nano-enabled formulations holds promise but requires scale-up and economic feasibility assessment.

Policy and regulatory gaps further constrain PGPR adoption. Harmonized quality standards, robust biosafety assessments, and farmer-centric extension programs are required to build confidence in PGPR-based products. Additionally, socio-economic studies evaluating cost-benefit ratios and adoption behavior are needed to facilitate large-scale deployment.

10. Conclusion

Plant Growth-Promoting Rhizobacteria represent a vital component of sustainable bio-input strategies for modern agriculture. Through a wide array of direct and indirect mechanisms, PGPR enhance nutrient availability, improve crop growth, mitigate abiotic and biotic stresses, and contribute to soil health and environmental sustainability. Their multifunctional nature positions them as effective alternatives or complements to conventional chemical fertilizers and pesticides.

This review critically examined recent advances in PGPR research, highlighting their mechanisms of action, role in nutrient use efficiency, stress tolerance, commercialization challenges, and emerging technological trends. While the benefits of PGPR are well established, inconsistent field performance, formulation constraints, regulatory challenges, and limited farmer awareness continue to hinder their large-scale adoption.

Future success of PGPR-based bio-inputs will depend on interdisciplinary research integrating microbiology, agronomy, formulation science, digital agriculture, and policy support. The development of region-specific, multi-trait PGPR consortia supported by omics-driven selection and precision application strategies will be key to improving reliability and scalability. With appropriate scientific, technological, and institutional interventions, PGPR can play a transformative role in advancing climate-smart, resource-efficient, and environmentally responsible agricultural systems.

Conflicts of Interest

The authors declare no conflicts of interest.

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