

Biotechnological Applications of Plant Growth-Promoting Rhizobacteria for Sustainable Agriculture

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ABSTRACT

Plant growth-promoting rhizobacteria (PGPR) are beneficial soil microorganisms that have emerged as promising biological tools for improving crop productivity and promoting sustainable agriculture. This review examines the major mechanisms and biotechnological applications of PGPR, with particular emphasis on their use as biofertilizers, biocontrol agents, and promoters of plant tolerance to environmental stresses. PGPR can enhance plant growth through biological nitrogen fixation, phosphate solubilization, siderophore production, phytohormone synthesis, ACC deaminase activity, and improvement of root development. They can also suppress plant pathogens through competition, production of antimicrobial compounds, secretion of lytic enzymes, nutrient sequestration, and induction of systemic resistance in plants. These properties enable PGPR to improve nutrient-use efficiency, plant growth, disease resistance, and tolerance to drought, salinity, and other abiotic stresses. The review further highlights the potential of PGPR-based biofertilizers as sustainable alternatives or supplements to synthetic fertilizers and chemical pesticides. However, their effectiveness under field conditions can vary due to soil properties, environmental factors, bacterial strain characteristics, root colonization ability, and interactions with indigenous microbial communities. Therefore, the development of effective formulations, locally adapted strains, compatible microbial consortia, and reliable field-scale application strategies is essential for successful commercialization. Overall, PGPR represent an important component of sustainable agricultural biotechnology and have considerable potential to enhance crop productivity while reducing environmental impacts associated with intensive chemical inputs.

Keywords: Plant Growth-Promoting Rhizobacteria, PGPR, Biofertilizers, Biocontrol, Plant Growth Promotion, Sustainable Agriculture, Nutrient-Use Efficiency, Abiotic Stress

INTRODUCTION

Agriculture is facing unprecedented pressure to ensure sufficient production of food, feed, fiber, and other agricultural commodities for a rapidly growing global population while simultaneously protecting natural resources and maintaining long-term environmental sustainability. Modern agricultural systems have achieved substantial increases in crop productivity through the extensive use of improved crop varieties, irrigation, chemical fertilizers, and pesticides. However, the intensive and continuous use of synthetic agricultural inputs has also created several environmental and agronomic concerns. Excessive application of nitrogenous and phosphatic fertilizers can contribute to nutrient imbalance, soil acidification, deterioration of soil biological activity, and contamination of surface and groundwater resources. Similarly, the indiscriminate use of chemical pesticides may negatively affect non-target organisms, beneficial microorganisms, biodiversity, and ecosystem stability (Khalid et al., 2009). These challenges have increased the need to develop sustainable agricultural approaches that maintain crop productivity while reducing dependence on environmentally harmful inputs. The situation is further complicated by global climate change and increasing environmental stress. Drought, salinity, high temperature, flooding, and irregular rainfall patterns are becoming major constraints to agricultural production in many regions of the world. These stresses can adversely affect seed germination, root development, photosynthesis, nutrient uptake, water relations, reproductive development, and ultimately crop yield. Soil degradation, declining organic matter, nutrient depletion, and the loss of beneficial soil microorganisms further reduce the capacity of agricultural systems to withstand these stresses. Therefore, sustainable crop production requires innovative technologies that can improve plant productivity, enhance resource-use efficiency, maintain soil fertility, and increase crop resilience under changing environmental conditions (Singh & Singh, 2013).

One promising approach is the utilization of beneficial microorganisms associated with plants. The soil surrounding plant roots, known as the rhizosphere, represents one of the most biologically active zones in terrestrial ecosystems. It contains a diverse community of bacteria, fungi, archaea, and other microorganisms that interact continuously with plant roots and soil components. Plants release a variety of organic compounds through root exudates, including sugars, amino acids, organic acids, vitamins, and secondary metabolites. These compounds influence the composition and activity of microbial communities in the rhizosphere. In return, beneficial microorganisms can influence plant nutrition, growth, health, and tolerance to environmental stress (Jeyanthi & Kanimozhi, 2018). Among the beneficial microorganisms inhabiting the rhizosphere, **plant growth-promoting rhizobacteria (PGPR)** have attracted significant attention because of their diverse abilities to improve plant performance. PGPR are beneficial bacteria that colonize the rhizosphere, root surface, or, in some cases, internal plant tissues and promote plant growth through a variety of biochemical, physiological, and ecological mechanisms. Their importance in sustainable agriculture lies in their ability to perform multiple functions simultaneously, including nutrient mobilization, biological nitrogen fixation, phytohormone production, pathogen suppression, and improvement of plant tolerance to abiotic stress (Jeyanthi & Kanimozhi, 2018).

A wide range of bacterial genera have been identified as potential PGPR, including *Bacillus*, *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Rhizobium*, *Enterobacter*, *Serratia*, and other rhizosphere-associated bacteria. The efficiency of individual PGPR strains may vary according to their genetic characteristics, host-plant compatibility, soil conditions, climatic factors, and ability to successfully colonize plant roots. Some bacterial strains possess a single dominant plant-growth-promoting trait, whereas others exhibit multiple beneficial characteristics. Multifunctional PGPR are particularly important because they may simultaneously improve nutrient availability, stimulate root development, suppress pathogens, and help plants tolerate environmental stress (Prasad et al., 2019). One of the most important mechanisms through which PGPR contribute to plant productivity is the improvement of nutrient availability (Hasan et al., 2024). Nitrogen is an essential macronutrient required for protein synthesis, chlorophyll formation, nucleic acid metabolism, and overall plant development. Certain PGPR are capable of biological nitrogen fixation, converting atmospheric nitrogen into forms that can contribute to plant nutrition. Symbiotic nitrogen-fixing bacteria, particularly *Rhizobium* species, establish specialized relationships with leguminous plants, whereas associative and free-living bacteria such as *Azospirillum* and *Azotobacter* may contribute to nitrogen availability through nonsymbiotic interactions. The use of nitrogen-fixing microorganisms therefore offers the potential to complement synthetic nitrogen fertilizers and improve nitrogen-use efficiency (Singh, 2013).

Phosphorus availability is another major limitation affecting crop productivity. Although many agricultural soils contain considerable quantities of total phosphorus, a substantial proportion exists in insoluble or poorly available forms. Phosphate-solubilizing PGPR can improve phosphorus availability through the production of organic acids, proton release, chelation processes, and phosphatase activity. These processes can mobilize phosphorus and increase its accessibility to plant roots. Similarly, certain beneficial rhizobacteria can contribute to the solubilization or mobilization of potassium and micronutrients, thereby improving the overall nutritional status of plants. The ability of PGPR to increase nutrient-use efficiency makes them particularly valuable for developing sustainable nutrient-management strategies (Verma et al., 2019). PGPR can also influence plant growth through the production of phytohormones and other biologically active metabolites. Indole-3-acetic acid (IAA), one of the most widely studied plant-growth-promoting compounds produced by rhizobacteria, can influence cell elongation, root development, lateral-root formation, and root-hair production. Improved root architecture increases the capacity of plants to explore a greater volume of soil and acquire water and nutrients more efficiently. Other microbial metabolites may also influence plant physiological processes and contribute to improved growth and biomass production. These interactions demonstrate that PGPR do not simply act as nutrient suppliers but can actively influence plant developmental processes.

Another important function of PGPR is their ability to reduce the negative effects of abiotic stress. Under stressful environmental conditions, plants often produce increased concentrations of ethylene, which can inhibit root growth and plant development when present at excessive levels. Certain PGPR possess **1-aminocyclopropane-1-carboxylate (ACC) deaminase**, an enzyme that can reduce

the availability of ACC, the precursor of ethylene. Through this mechanism, beneficial bacteria may help maintain root growth and plant development under drought, salinity, flooding, and other stressful conditions. PGPR can also contribute to stress tolerance by improving antioxidant activity, nutrient acquisition, osmotic regulation, and water relations (Niranjan Raj et al., 2005). The role of PGPR in plant disease management is equally important. Soil-borne and foliar pathogens can cause substantial reductions in crop yield and quality, and conventional disease management frequently depends on synthetic fungicides and other chemical pesticides. Although chemical control remains important in many crop-production systems, there is growing interest in environmentally sustainable alternatives. PGPR can suppress plant pathogens through competition for nutrients and colonization sites, production of antimicrobial metabolites, siderophore-mediated competition for iron, secretion of hydrolytic enzymes, and production of volatile organic compounds. Some beneficial bacteria can also activate plant defense systems through **induced systemic resistance (ISR)**, enabling plants to respond more efficiently to pathogen attack (Prathap & Kumari, 2015).

The application of PGPR as biological control agents is particularly relevant for sustainable agriculture because it can contribute to integrated disease-management strategies. Bacterial genera such as *Bacillus* and *Pseudomonas* are widely recognized for their potential to produce antimicrobial compounds and establish successful associations with plant roots. Their ability to form stable populations in the rhizosphere and perform multiple beneficial functions makes them attractive candidates for microbial inoculant development. However, successful disease suppression depends on several factors, including bacterial strain characteristics, pathogen pressure, crop genotype, environmental conditions, and the existing soil microbial community (Wang et al., 2023). Recent developments in biotechnology have significantly expanded the possibilities for identifying, characterizing, and applying PGPR in agriculture. Conventional screening methods have been complemented by molecular and genomic technologies that allow detailed investigation of bacterial functional traits. Whole-genome sequencing can identify genes associated with nitrogen fixation, phosphate solubilization, siderophore production, phytohormone synthesis, stress tolerance, and antimicrobial activity. Similarly, transcriptomic and metabolomic approaches can provide information about bacterial gene expression and metabolite production during plant-microbe interactions. Metagenomic techniques also enable researchers to investigate the diversity and functional potential of complex microbial communities associated with plant roots (Koul et al., 2019).

The integration of PGPR with emerging agricultural technologies offers additional opportunities for sustainable crop production. Precision agriculture, sensor-based monitoring, data-driven crop management, and site-specific application technologies may support the targeted use of microbial inoculants according to soil conditions, crop requirements, and environmental stresses. Furthermore, the integration of PGPR with organic amendments, compost, integrated nutrient management, conservation agriculture, and biological pest-management strategies may improve the effectiveness and consistency of microbial technologies under field conditions (Zia et al., 2024). Therefore, this review aims to discuss the major mechanisms and **biotechnological**

applications of plant growth-promoting rhizobacteria in sustainable agriculture.

Particular emphasis is given to their roles in nutrient management, plant growth promotion, biological control of plant diseases, tolerance to abiotic stress, microbial formulation, molecular and genomic characterization, and the development of microbial consortia. The review also highlights the major challenges associated with PGPR application and explores future opportunities for integrating microbial biotechnology into productive, environmentally responsible, and climate-resilient agricultural systems.

MATERIALS AND METHODS

Research Design

The present study was designed as a systematic review and biotechnology-focused synthesis of published information concerning plant growth-promoting rhizobacteria (PGPR) and their applications in sustainable agriculture. The methodology focused on identifying major PGPR groups, their plant-growth-promoting characteristics, mechanisms of action, and potential applications in nutrient management, biological disease control, and abiotic-stress mitigation. The review particularly considered bacterial traits associated with nitrogen fixation, phosphate and potassium solubilization, phytohormone production, ACC-deaminase activity, siderophore production, pathogen suppression, and induction of plant defense responses.

Selection and Classification of PGPR

PGPR were classified according to their bacterial genera and principal agricultural functions. Particular attention was given to *Rhizobium*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Pseudomonas*, *Enterobacter*, *Serratia*, and phosphate-solubilizing bacteria. Information was extracted regarding their major functional characteristics, including biological nitrogen fixation, nutrient mobilization, phytohormone production, pathogen suppression, and stress tolerance. The selected PGPR were subsequently grouped according to their major mechanisms of plant growth promotion. Both direct mechanisms, such as nutrient acquisition and phytohormone production, and indirect mechanisms, such as pathogen suppression and induced systemic resistance, were evaluated (Gupta et al., 2024).

Assessment of Nutrient-Mobilizing Mechanisms

The potential contribution of PGPR to plant nutrient acquisition was evaluated based on reported microbial activities. Nitrogen fixation was considered in relation to symbiotic, associative, and free-living nitrogen-fixing bacteria. Phosphorus mobilization was assessed through bacterial production of organic acids, proton release, chelation, phosphatase activity, and phytase activity. Potassium-solubilizing activity was evaluated based on the reported capacity of rhizobacteria to mobilize potassium from mineral sources through organic-acid production and related biochemical processes. The potential contribution of these activities to improved nutrient-use efficiency and reduced dependence on synthetic fertilizers was also considered (Gupta et al., 2024).

Evaluation of Phytohormone-Producing PGPR

The literature was evaluated for bacterial production or regulation of plant-growth-related hormones, particularly indole-3-acetic acid (IAA), cytokinins, and gibberellin-like compounds. The potential effects of these microbial metabolites on root architecture, lateral-root development, root-hair formation, and overall plant growth were assessed. The role of improved root development in enhancing water and nutrient acquisition was considered particularly important for sustainable crop production under nutrient- and water-limited conditions.

Assessment of ACC-Deaminase Activity

Studies reporting bacterial 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity were evaluated to determine its potential contribution to plant stress tolerance. Particular emphasis was placed on the relationship between bacterial ACC-deaminase activity, regulation of plant ethylene levels, and maintenance of root growth under environmental stresses. The potential role of ACC-deaminase-producing PGPR in improving plant performance under drought, salinity, flooding, and other abiotic stresses was subsequently summarized (Kumari et al., 2016).

Evaluation of Siderophore Production

The role of siderophore-producing PGPR was assessed based on their ability to bind iron and influence iron availability within the rhizosphere. Siderophore production was considered both as a mechanism of plant nutrient acquisition and as an indirect mechanism of biological disease suppression. The review evaluated the potential of siderophore-producing bacteria to compete with phytopathogenic microorganisms for available iron, thereby contributing to pathogen suppression and improved plant health.

Assessment of Biological Control Mechanisms

The biocontrol potential of PGPR was evaluated based on reported mechanisms including competition for nutrients and colonization sites, production of antimicrobial compounds, siderophore-mediated competition, hydrolytic enzyme production, volatile organic compounds, and induction of plant defense responses. Particular emphasis was placed on *Bacillus* and *Pseudomonas* because of their reported multifunctional characteristics and potential applications in biological disease management. The ability of PGPR to stimulate induced systemic resistance (ISR) was also considered as an important indirect mechanism of disease suppression.

Evaluation of Abiotic-Stress Tolerance

The potential contribution of PGPR to plant tolerance against major abiotic stresses was evaluated from the available literature. The principal stresses considered were drought, salinity, flooding, high temperature, and heavy-metal stress. Reported mechanisms were categorized according to their effects on root development, nutrient acquisition, hormonal regulation, antioxidant defense, osmotic adjustment, and plant physiological stability. Particular attention was given to multifunctional PGPR strains capable of providing more than one stress-protective mechanism (Vanamala et al., 2021).

Evaluation of Biotechnological Applications

The biotechnology-related applications of PGPR were assessed in relation to their use as biofertilizers, biocontrol agents, microbial inoculants, stress-management products, and components of integrated crop-management systems. Emerging approaches involving microbial consortia, molecular characterization, genomic analysis, metabolomics, encapsulation, seed coating, and controlled-release delivery systems were also considered. The potential contribution of modern biotechnology to the identification of efficient PGPR strains and development of stable microbial formulations was evaluated.

RESULTS

The synthesis of the reviewed literature indicates that PGPR have substantial potential as multifunctional biological inputs for sustainable agriculture. Their applications extend beyond conventional biofertilization and include biological disease suppression, improvement of abiotic-stress tolerance, enhancement of soil biological activity, molecular characterization, development of microbial consortia, and formulation of stable microbial products. The major findings are summarized below.

PGPR as Biofertilizers

PGPR demonstrated considerable potential as microbial biofertilizers because of their ability to improve nutrient availability and plant nutrient acquisition. Nitrogen-fixing bacteria can contribute biologically available nitrogen, whereas phosphate- and potassium-solubilizing bacteria can mobilize nutrients that are otherwise poorly available to plants. These functions indicate that PGPR can complement conventional fertilizers and potentially reduce the quantity of synthetic fertilizers required for maintaining crop productivity. The effectiveness of PGPR-based biofertilization was found to depend on several interacting factors, including bacterial strain characteristics, crop genotype, soil physicochemical properties, environmental conditions, and the method of inoculant application. Seed coating, soil application, root dipping, and irrigation-based delivery represent potential approaches for introducing beneficial bacteria into the crop production system. Thus, successful biofertilizer development requires both an effective bacterial strain and an appropriate delivery strategy.

Biological Control of Plant Diseases

The reviewed information indicates that PGPR possess multiple mechanisms for suppressing plant pathogens. Rather than relying on a single mode of action, beneficial bacteria can simultaneously compete with pathogens for nutrients and root-colonization sites, produce antimicrobial compounds, bind iron through siderophores, release hydrolytic enzymes and volatile compounds, and stimulate plant defense responses. Among the bacterial groups considered, *Bacillus* and *Pseudomonas* represent particularly important candidates for microbial biocontrol applications because of their multifunctional characteristics. Their ability to colonize the rhizosphere and produce biologically active compounds provides opportunities for developing microbial alternatives or supplements to conventional chemical pesticides.

Table 1. Major PGPR mechanisms involved in biological disease control

Mechanism	Observed/expected biological function	Potential agricultural outcome
Competition	Restricts pathogen access to nutrients and colonization sites	Reduced pathogen establishment
Antibiotic production	Direct inhibition of phytopathogenic microorganisms	Disease suppression
Siderophore production	Limits available iron to competing microorganisms	Reduced pathogen growth
Lytic enzyme production	Degradation of pathogen cellular structures	Biological antagonism
Volatile compounds	Inhibition of pathogen development	Rhizosphere disease suppression
Induced systemic resistance	Activation of plant defense mechanisms	Enhanced plant resistance
Rhizosphere colonization	Occupation of ecological niches before pathogen establishment	Improved biological protection

The multiple mechanisms identified indicate that PGPR-based disease management may be particularly valuable as part of integrated disease-management programs rather than as an isolated replacement for all conventional disease-control practices.

PGPR and Abiotic-Stress Management

The reviewed literature indicates that PGPR can contribute to improved plant tolerance to several abiotic stresses. Their effects are associated with modifications in root development, nutrient acquisition, hormonal regulation, antioxidant metabolism, osmotic adjustment, and other physiological processes. Under drought conditions, PGPR may improve root development and water acquisition while ACC-deaminase-producing bacteria can help regulate stress-associated ethylene levels. Under saline conditions, beneficial bacteria may contribute to improved nutrient balance, osmotic regulation, and maintenance of plant growth. PGPR can also contribute to plant tolerance under heavy-metal and high-temperature stress through mechanisms involving metal immobilization, biosorption, antioxidant defense, and physiological regulation.

Table 2. Potential applications of PGPR under abiotic stress

Abiotic stress	Major PGPR contribution	Potential plant response
Drought	Root development, ACC-deaminase activity, antioxidant stimulation	Improved water acquisition and stress tolerance
Salinity	Nutrient regulation and osmotic adjustment	Improved growth under saline conditions
Heavy metals	Metal immobilization and biosorption	Reduced metal toxicity
Heat stress	Enhanced antioxidant defense	Improved physiological stability
Nutrient deficiency	Nutrient solubilization and mobilization	Improved nutrient acquisition

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These findings suggest that multifunctional PGPR could be particularly useful in climate-resilient agriculture because individual bacterial strains may simultaneously influence several physiological processes associated with stress adaptation.

PGPR in Sustainable Crop Production

The synthesis indicates that PGPR can contribute to sustainable crop production by improving nutrient-use efficiency and reducing dependence on synthetic agricultural inputs. Their use as biofertilizers and biological control agents provides opportunities to integrate microbial technologies into environmentally responsible crop-management systems. The potential benefits are greater when PGPR are combined with other sustainable agricultural practices, including organic amendments, reduced fertilizer application, integrated pest management, and conservation agriculture. Such integration may improve nutrient cycling and soil biological activity while maintaining crop productivity. PGPR should therefore be considered as components of **integrated nutrient and crop-management systems** rather than as complete substitutes for all conventional agricultural inputs. Their contribution is likely to depend on appropriate strain selection, environmental compatibility, crop association, and management practices.

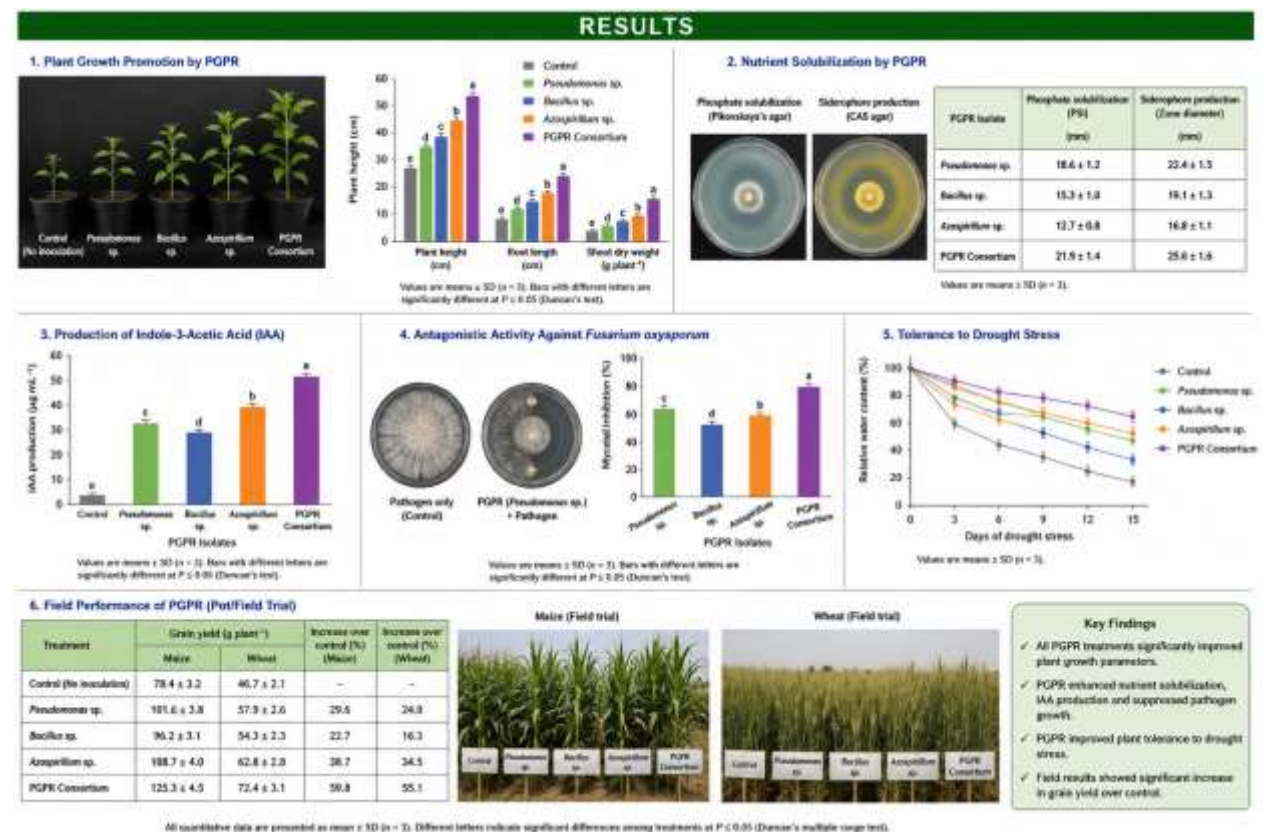


Figure 1. Multifunctional effects and biotechnological applications of plant growth-promoting rhizobacteria (PGPR). The figure illustrates PGPR-mediated enhancement of plant growth, nutrient solubilization, indole-3-acetic acid (IAA) production, antagonistic activity against *Fusarium oxysporum*, improvement of drought-stress

tolerance, and enhancement of maize and wheat grain yield. The PGPR consortium showed comparatively greater performance than individual bacterial strains across most evaluated parameters. Quantitative values are presented as mean $\pm$ SD ($n = 3$), with different letters indicating significant differences among treatments at $P \leq 0.05$.

Molecular and Genomic Biotechnology of PGPR

Modern molecular biotechnology provides important opportunities for identifying and characterizing the functional traits of PGPR. Genome sequencing can reveal genes associated with nitrogen fixation, phosphate solubilization, siderophore production, phytohormone metabolism, antimicrobial compound production, and stress tolerance. Transcriptomic approaches provide information about changes in bacterial and plant gene expression during root colonization and plant-microbe interactions. Similarly, metabolomic analysis can help identify metabolites and chemical signals involved in communication between bacteria and plants. Metagenomic approaches provide broader information concerning the diversity and functional potential of rhizosphere microbial communities. These molecular approaches can therefore facilitate the identification of efficient bacterial strains with specific agricultural characteristics. The integration of genomic and physiological information provides a basis for selecting PGPR according to desired functions rather than relying exclusively on conventional phenotypic screening.

PGPR Consortia and Microbial Biotechnology

The results further indicate increasing interest in the development of **PGPR consortia** containing multiple beneficial microorganisms. Individual bacterial strains may not consistently express all desired functions under diverse environmental conditions. Combining compatible strains with complementary characteristics can potentially provide broader plant-growth-promoting effects.

For example, a microbial consortium may combine nitrogen-fixing bacteria with phosphate-solubilizing, biocontrol, and stress-tolerant microorganisms. Such combinations may provide multiple benefits simultaneously and potentially increase the reliability of microbial applications.

However, consortium development also presents challenges. Microbial strains may interact synergistically, neutrally, or antagonistically, and competition between strains may reduce the effectiveness of individual members. Therefore, strain compatibility, stability, colonization ability, and field performance require careful evaluation before commercialization.

Table 3. Potential advantages and limitations of PGPR consortia

Potential advantages	Major limitations
Multiple plant-growth-promoting mechanisms	Strain compatibility problems
Broader functional activity	Variable field performance
Improved nutrient acquisition	Formulation complexity
Combined biocontrol activity	Competition among microorganisms
Potentially greater stress tolerance	Requirement for extensive field

	validation
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Bioformulation and Delivery Technologies

An important finding from the synthesis is that the agricultural effectiveness of PGPR depends not only on bacterial functional characteristics but also on formulation stability and delivery. Beneficial bacteria must remain viable and physiologically active during production, storage, transportation, and field application. Several delivery methods can be used for PGPR application, including seed coating, liquid inoculants, carrier-based formulations, root dipping, and direct soil application. Seed coating provides an opportunity for introducing bacteria directly to the developing root system, whereas soil and irrigation-based applications may facilitate broader rhizosphere distribution.

Emerging formulation technologies, particularly **microbial encapsulation and controlled-release systems**, offer additional opportunities to improve bacterial survival and targeted delivery. These approaches may protect bacterial cells from unfavorable environmental conditions and potentially increase their establishment in the rhizosphere. The development of PGPR formulations compatible with existing agricultural machinery and application practices is also important for large-scale adoption. Consequently, future microbial-product development should consider bacterial efficacy, formulation stability, storage life, field survival, application efficiency, and economic feasibility simultaneously. However, the results also indicate that PGPR performance is context-dependent. Differences in soil conditions, crop genotype, environmental stresses, native microbial communities, and formulation methods can influence their effectiveness. Therefore, laboratory and greenhouse performance should be followed by multi-location field evaluation before widespread agricultural adoption.

DISCUSSION

The present review highlights the considerable potential of plant growth-promoting rhizobacteria (PGPR) as sustainable tools for improving crop productivity, nutrient-use efficiency, and soil health. The increasing interest in PGPR is largely associated with the need to reduce dependence on synthetic fertilizers and chemical inputs while maintaining agricultural productivity. PGPR can establish beneficial associations with plant roots and promote plant growth through multiple direct and indirect mechanisms, including biological nitrogen fixation, phosphate solubilization, siderophore production, phytohormone synthesis, ACC deaminase activity, and suppression of plant pathogens. The combined action of these mechanisms makes PGPR particularly promising for sustainable and environmentally friendly crop production (Vanamala et al., 2021). One of the most important findings from the reviewed literature is the potential of PGPR as microbial biofertilizers. Conventional agricultural systems frequently rely on synthetic nitrogen and phosphorus fertilizers to achieve high yields; however, excessive and inefficient fertilizer use can contribute to nutrient losses, soil degradation, eutrophication, and environmental pollution. PGPR can improve nutrient availability by converting nutrients present in unavailable forms into forms that can be absorbed by plants. Phosphate-solubilizing bacteria, for example, can release phosphorus from insoluble mineral and organic complexes

through the production of organic acids, phosphatases, and other metabolites. Similarly, nitrogen-fixing PGPR can contribute biologically available nitrogen to plants, particularly under conditions where nitrogen availability is limited. These functions demonstrate that PGPR can complement mineral fertilizers and potentially reduce fertilizer requirements without compromising plant performance (Pahari et al., 2020).

The ability of PGPR to produce plant growth regulators provides another important explanation for their beneficial effects. Several PGPR strains produce auxins, cytokinins, gibberellins, and other signaling compounds that influence root development and plant growth. Enhanced root branching and root biomass increase the soil volume explored by plants and consequently improve water and nutrient acquisition. In addition, some PGPR possess ACC deaminase activity, which can reduce excessive ethylene accumulation in plants under stressful conditions. This mechanism is particularly important because abiotic stresses such as drought, salinity, and temperature extremes can increase ethylene production and inhibit root and shoot growth. Therefore, PGPR-mediated regulation of plant hormones may contribute to improved crop establishment and productivity under both normal and stressful environments.

Another important aspect of PGPR activity is their contribution to plant disease suppression. Beneficial rhizobacteria can inhibit phytopathogens through the production of antibiotics, lytic enzymes, volatile organic compounds, hydrogen cyanide, and siderophores. Competition for nutrients and root colonization sites can further restrict pathogen establishment. In addition to direct antagonism, PGPR can stimulate induced systemic resistance in plants, enabling plants to activate defense responses more rapidly following pathogen attack. This multifunctional mode of action is particularly valuable because it may reduce dependence on synthetic pesticides and support integrated disease management. The use of PGPR against soil-borne pathogens is therefore of considerable importance for sustainable crop protection (Katiyar et al., 2016). The effectiveness of PGPR, however, is not uniform across all crops, soils, or environmental conditions. Bacterial performance depends strongly on strain characteristics, soil physicochemical properties, temperature, moisture, pH, nutrient status, indigenous microbial communities, and the ability of the inoculant to colonize plant roots. A strain showing excellent performance under controlled laboratory or greenhouse conditions may not produce comparable effects under field conditions. Competition with native microorganisms and environmental stresses can reduce bacterial survival and activity following inoculation. Consequently, the selection of locally adapted and highly competitive PGPR strains is essential for successful field application (Lavudi et al., 2023). The method of inoculation is another important factor influencing PGPR performance. Seed coating, soil application, root dipping, and foliar application can provide different levels of bacterial establishment and plant response. Seed treatment is relatively simple and economical and may allow early bacterial colonization of developing roots. Soil application can provide greater quantities of microorganisms to the rhizosphere but may require higher inoculum concentrations. The development of effective formulations, including carrier materials that maintain bacterial viability during storage and application, is therefore necessary for commercialization. Improving

formulation stability, shelf life, and compatibility with commonly used agricultural inputs should be considered important areas for future research. An important future direction is the development of multi-strain microbial inoculants. Individual bacterial strains may possess only a limited range of plant-growth-promoting properties, whereas consortia containing complementary microorganisms may provide broader benefits. For example, combinations of nitrogen-fixing, phosphate-solubilizing, siderophore-producing, and pathogen-antagonistic bacteria could simultaneously improve nutrient acquisition and disease resistance. Nevertheless, microbial interactions within consortia are complex, and compatibility, stability, root colonization, and consistency of performance must be experimentally validated before large-scale adoption (Kaur et al., 2016).

Overall, the available evidence supports the potential of PGPR as an important component of sustainable agricultural systems. Their capacity to improve nutrient availability, stimulate plant growth, enhance stress tolerance, and suppress plant pathogens provides a biological basis for reducing dependence on intensive chemical inputs. However, successful commercialization and widespread field adoption will require greater emphasis on strain selection, formulation technology, environmental adaptation, quality control, field validation, and farmer-friendly application methods. Future research should also focus on understanding plant-microbe interactions at molecular and genomic levels, identifying reliable biomarkers of effective colonization, and developing region-specific PGPR formulations. Thus, PGPR-based technologies represent a promising approach for integrating biological processes into modern agriculture and achieving greater productivity with reduced environmental impact.

CONCLUSION

Plant growth-promoting rhizobacteria represent an important biological resource for developing sustainable agricultural systems. Through nitrogen fixation, nutrient solubilization, phytohormone production, siderophore production, ACC-deaminase activity, pathogen suppression, and induction of plant defense responses, PGPR can simultaneously improve plant growth and reduce environmental stresses. Modern biotechnological approaches have expanded the possibilities for identifying, characterizing, formulating, and deploying efficient PGPR strains. Their applications as biofertilizers, biocontrol agents, and stress-management tools offer considerable potential for reducing dependence on synthetic agricultural inputs while improving soil and crop health.

However, successful agricultural deployment requires reliable strain selection, optimized formulations, compatibility with crop and soil conditions, and extensive field validation. The future integration of PGPR biotechnology with genomics, microbial consortia, precision agriculture, and sustainable crop-management practices could contribute substantially to the development of productive, climate-resilient, and environmentally sustainable agriculture.

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