**Role of Plant Growth Promoting Rhizobacteria for Advanced Sustainable Agricultural Practices: A Review**

**Abstract**

This review explores the role of PGPR in nutrient cycling, soil structure improvement, and soil pH modification. Traditional agriculture relies heavily on chemical inputs, which pose significant threats to the environment and deplete natural resources. The environmental challenges posed by chemical-based agriculture and emphasize the urgent need for sustainable alternatives in the face of climate change. Plant Growth-Promoting Rhizobacteria (PGPR) are beneficial soil microorganisms that enhance plant growth through various direct and indirect mechanisms, offering a sustainable approach to improving soil fertility and crop productivity. PGPR have emerged as a sustainable alternative, fostering plant development, and enhancing stress resilience. A comprehensive understanding of the underlying signalling pathways and stress management mechanisms is essential to maximizing their potential. Plant health has been demonstrated, nutrient uptake has improved, and environmental stress has been reduced with the help of PGPR. PGPR facilitate nitrogen fixation, phosphorus and potassium solubilization, and organic matter decomposition, enhancing nutrient availability and promoting plant growth. Their ability to produce exopolysaccharides contributes to soil aggregation, improving soil structure and water retention. Additionally, PGPR modifies rhizosphere pH, enhancing nutrient solubility and availability. PGPR also promote crop yield by enhancing root and shoot growth, improving seed germination, and increasing stress tolerance against drought, salinity, and heavy metal contamination. Moreover, PGPR provides effective biocontrol against pathogens through antibiosis, competition, and induced systemic resistance (ISR), contributing to improved crop resilience. Despite their potential, several challenges hinder the widespread adoption of PGPR, including inconsistent field performance, limited shelf-life, compatibility issues with native soil microbiota, and regulatory barriers. Emerging approaches such as genetic engineering, multi-strain consortia, and nano-formulations are being developed to enhance PGPR efficacy and stability under diverse environmental conditions. Integrating PGPR with organic and chemical fertilizers presents a promising strategy for achieving higher yields while minimizing environmental impact. Future research should focus on understanding PGPR-plant signalling pathways, optimizing formulation techniques, and developing policies to promote their commercial use. Collaborative efforts between researchers, industries, and policymakers are essential to enhance the application of PGPR in sustainable agriculture. Widespread adoption of PGPR-based technologies could significantly contribute to global food security, environmental sustainability, and the reduction of chemical inputs in agriculture. This review highlights the potential of PGPR as a valuable tool for enhancing agricultural productivity through environmentally friendly practices. Future research should focus on developing efficient, cost-effective formulations and enhancing collaboration between researchers, policymakers, and industries to ensure global food security and environmental sustainability.

**Keywords:** *Plant Growth-Promoting Rhizobacteria, Soil Fertility, Crop Yield, Biocontrol, Nutrient Cycling, Sustainable Agriculture, Biofertilizers.*

**I. Introduction**

**A. Information**

*Importance of soil fertility and crop yield in agriculture.*  
Soil fertility is a critical factor in determining the productivity of agricultural systems (Watson *et.al.,* 2002). It refers to the soil's ability to supply essential nutrients in adequate amounts and proper proportions for optimal plant growth. Maintaining soil fertility is vital for achieving high crop yields and ensuring food security worldwide. Intensive farming practices aimed at increasing crop productivity have led to the overuse of chemical fertilizers, which poses severe threats to soil health and environmental sustainability. The global demand for food production is expected to increase by 70% by 2050, exerting significant pressure on natural resources, including soil quality.

*Challenges in conventional agricultural practices (e.g., overuse of chemical fertilizers).*  
The excessive application of chemical fertilizers has resulted in soil degradation, nutrient imbalances, and reduced microbial diversity in the rhizosphere (Pahalvi *et.al.,* 2021). Overuse of nitrogenous fertilizers contributes to soil acidification, which negatively impacts soil structure and fertility. Moreover, chemical inputs have detrimental effects on beneficial soil microorganisms that play a crucial role in nutrient cycling. Studies have indicated that prolonged use of synthetic fertilizers leads to nutrient leaching, groundwater contamination, and decreased crop resilience against environmental stressors. The need for sustainable agricultural practices has driven researchers to explore eco-friendly alternatives, such as Plant Growth-Promoting Rhizobacteria (PGPR).

**B. Plant Growth-Promoting Rhizobacteria (PGPR)**

*Definition of PGPR.*  
Plant Growth-Promoting Rhizobacteria (PGPR) are a diverse group of soil bacteria that actively colonize plant roots and stimulate plant growth through various direct and indirect mechanisms (Jha *et.al.,* 2015). These bacteria are known for their ability to enhance nutrient availability, produce phytohormones, and protect plants from pathogens, making them a valuable resource for sustainable agriculture.

*Brief history of PGPR research.*  
Research on PGPR dates back to the early 20th century when scientists first observed beneficial interactions between soil microorganisms and plants. The term “PGPR” describes bacteria that enhance plant growth through rhizospheric interactions. Since then, extensive studies have focused on the identification, characterization, and application of PGPR for promoting crop productivity. Recent advancements in molecular biology and biotechnology have facilitated a deeper understanding of the mechanisms underlying PGPR-plant interactions, providing new opportunities for their commercial exploitation. PGPR creates antimicrobial substances that prevent the development of plant diseases. By competing with pathogenic microbes for nutrients and space in the root zone, these helpful bacteria decrease the possibility of disease establishment. PGPR serve a crucial role in preventing illness, lowering the need for chemical pesticides, and encouraging healthier and more robust crops by activating the plant's defence mechanisms and directly suppressing pathogens (Tripathi et al., 2024). By aiding in nutrient absorption, stimulating root growth, and providing protection against harmful organisms, PGPR can increase crop yield and minimize reliance on synthetic fertilizers and pesticides. Without a doubt, PGPRs is a step toward organic farming. Organic farming is highly successful for crop production since it reduces the need for chemical inputs (Raza et al., 2024; Shivashakarappa et al., 2022; Kumar et al., 2024).

**C. Purpose of the Review**

*To evaluate the role of PGPR in enhancing soil fertility and crop productivity.*  
The primary aim of this review is to evaluate the effectiveness of PGPR in improving soil fertility and enhancing crop yield through various mechanisms such as nitrogen fixation, phosphate solubilization, siderophore production, and pathogen suppression (Bhardwaj *et.al.,* 2014). Understanding the functional diversity of PGPR can aid in developing biofertilizers that are environmentally friendly and economically viable.

*To summarize recent advancements and prospects.*  
This review also seeks to provide a comprehensive overview of recent research findings related to PGPR, highlighting novel strains and formulations that have demonstrated promising results in field trials. Moreover, potential challenges associated with PGPR application and future research directions aimed at enhancing their effectiveness will be discussed.

**II. Plant Growth-Promoting Rhizobacteria (PGPR): Mechanisms and Diversity**

**A. Classification of PGPR**

*Free-living PGPR.*  
Free-living PGPR are non-symbiotic bacteria that exist independently in the soil and colonize the rhizosphere, enhancing plant growth through various mechanisms. Common examples include *Pseudomonas, Bacillus, and Azotobacter* species. These bacteria are known for their efficiency in producing phytohormones and solubilizing phosphorus, contributing significantly to nutrient availability. Studies have shown that *Bacillus subtilis* can enhance wheat growth by improving nutrient uptake and promoting root elongation (Ilyas *et.al.,* 2022).

*Symbiotic PGPR.*  
Symbiotic PGPR establishes mutualistic relationships with host plants, typically forming nodules or other specialized structures. The most well-known symbiotic PGPR are *Rhizobium* and *Bradyrhizobium*, which form nitrogen-fixing nodules on legume roots. Research has demonstrated that *Rhizobium* inoculation in legumes can increase nitrogen content in the soil by approximately 30-40 kg N/ha per cropping season. Symbiotic PGPR plays a vital role in sustainable agriculture by minimizing the need for chemical nitrogen fertilizers (Gupta *et.al.,* 2015).

*Endophytic PGPR.*  
Endophytic PGPR reside within plant tissues without causing harm to the host (Sekar *et.al.,* 2010). These bacteria colonize internal plant tissues and provide beneficial effects, such as enhanced growth, stress tolerance, and disease resistance. Examples include *Azospirillumbrasilense* and *Burkholderiaphytofirmans*, which have demonstrated positive effects on cereals and other crops by promoting root growth and improving nutrient absorption. Studies have reported yield increases of up to 30% in wheat and maize when treated with endophytic *Azospirillum* strains.

**B. Mechanisms of Action**

*Direct Mechanisms*

* *Nitrogen fixation.*  
  Nitrogen fixation is a critical mechanism through which PGPR contribute to soil fertility. Nitrogen-fixing PGPR, particularly *Rhizobium* and *Azospirillum*, convert atmospheric nitrogen (N₂) into ammonia (NH₃), making it available for plant uptake. Biological nitrogen fixation contributes approximately 100-290 million metric tons of nitrogen per year globally. Studies have shown that *Azospirillum* inoculation can enhance nitrogen uptake in wheat by 20-30%.
* *Phosphate solubilization.*  
  Phosphorus is a vital nutrient often present in insoluble forms, making it unavailable to plants. PGPR such as *Pseudomonas, Bacillus, and Rhizobium* possess the ability to solubilize inorganic phosphate by producing organic acids (Rawat *et.al.,* 2021). Research indicates that phosphate-solubilizing bacteria can increase phosphorus availability by 40-50%. This enhanced phosphorus availability leads to improved plant growth and higher crop yields.
* *Production of plant growth regulators (Auxins, Cytokinins, Gibberellins).*  
  PGPR synthesize various plant growth regulators that promote cell division, elongation, and root growth. Indole-3-acetic acid (IAA) is the most commonly produced auxin by PGPR such as *Pseudomonas fluorescens* and *Azospirillumbrasilense*. Studies have reported IAA production levels ranging from 20 to 80 µg/mL depending on the bacterial strain and environmental conditions.
* *Siderophore production.*  
  Siderophores are iron-chelating compounds produced by PGPR to sequester iron from the environment, making it available to plants (Pahari *et.al.,* 2017). *Pseudomonas* and *Bacillus* species are known for their siderophore production capabilities. The ability of siderophores to enhance iron uptake can significantly improve plant health and productivity, especially in iron-deficient soils.

*Indirect Mechanisms*

* *Biocontrol of plant pathogens.*  
  PGPR suppress plant pathogens through mechanisms such as antibiosis, competition for nutrients, and enzyme production (Pathak *et.al.,* 2017). *Pseudomonas fluorescens* has been widely studied for its ability to produce antibiotics like phenazine, pyoluteorin, and 2,4-diacetylphloroglucinol (DAPG), which inhibit pathogenic fungi and bacteria.
* *Induced systemic resistance (ISR).*  
  ISR is a defence mechanism activated by PGPR, enhancing the plant’s resistance against various pathogens. This mechanism involves the production of signalling molecules like salicylic acid and jasmonic acid, which trigger systemic immune responses in plants. *Bacillus subtilis* has been reported to induce ISR in tomato plants against *Fusarium* wilt, leading to a 60-70% reduction in disease incidence.
* *Competitive exclusion of pathogens.*  
  PGPR can outcompete pathogenic microorganisms for nutrients and ecological niches in the rhizosphere (Wang *et.al.,* 2021). This competition prevents the establishment and proliferation of harmful pathogens, enhancing plant health and growth.

**C. Diversity of PGPR**

*Taxonomic diversity (e.g., Bacillus, Pseudomonas, Azospirillum, Rhizobium).*  
PGPR encompass a wide range of bacterial taxa, with *Bacillus, Pseudomonas, Azospirillum,* and *Rhizobium* being the most commonly studied genera. *Bacillus* and *Pseudomonas* are known for their resilience and ability to produce various metabolites that enhance plant growth.

*Ecological distribution (Soil types, climatic conditions).*  
PGPR diversity is influenced by factors such as soil type, pH, temperature, moisture content, and cropping practices (Landa *et.al.,* 2012). These bacteria are found in various environments, including agricultural soils, forest soils, and arid regions. The ability of PGPR to adapt to diverse environmental conditions is crucial for their successful application as biofertilizers.

**III. Role of PGPR in Enhancing Soil Fertility**

**A. Nutrient Cycling**

*Nitrogen fixation.*  
Nitrogen is a crucial nutrient for plant growth, yet most crops cannot utilize atmospheric nitrogen directly (Leghari *et.al.,* 2016). PGPR play a significant role in biological nitrogen fixation, where atmospheric nitrogen (N₂) is converted into ammonia (NH₃) through the activity of the nitrogenase enzyme complex. Free-living and symbiotic nitrogen-fixing bacteria such as *Azospirillum, Rhizobium, Bradyrhizobium, and Frankia* are known for their nitrogen-fixing capabilities. Studies indicate that *Rhizobium* species contribute approximately 20–300 kg N/ha per year through biological nitrogen fixation in leguminous crops. *Azospirillumbrasilense* inoculation has been shown to increase nitrogen content in maize by 30%, resulting in a yield improvement of up to 15%. The global contribution of biological nitrogen fixation by PGPR is estimated to be around 100–290 million metric tons of nitrogen annually.

*Phosphorus and potassium solubilization.*  
Phosphorus is the second most critical macronutrient after nitrogen for plant growth, yet it is often present in insoluble forms that are unavailable for plant uptake (Malhotra *et.al.,* 2018). Phosphate-solubilizing bacteria (PSB), including *Pseudomonas, Bacillus, Rhizobium, and Enterobacter*, produce organic acids such as gluconic, citric, and malic acids, which convert insoluble phosphates into bioavailable forms. Research has demonstrated that inoculation with *Bacillus megaterium* increases available phosphorus by up to 50% and enhances crop yields by 20%.  
Potassium-solubilizing bacteria (KSB) are also essential for nutrient cycling. Species such as *Bacillus mucilaginosus* and *Frateuria aurantia* release potassium from minerals like mica, feldspar, and illite, improving potassium availability in soil. KSB inoculation has been reported to enhance potassium uptake in wheat by 10–20%, leading to improved biomass production.

*Organic matter decomposition.*  
PGPR contribute to organic matter decomposition by producing extracellular enzymes such as cellulases, proteases, and chitinases (Reddy *et.al.,* 2022). These enzymes break down complex organic materials into simpler forms, releasing essential nutrients like nitrogen, phosphorus, and sulfur. The decomposition process improves soil fertility by enhancing nutrient availability and promoting soil organic carbon content. Studies have shown that *Bacillus subtilis* and *Pseudomonas fluorescens* are effective in decomposing crop residues, leading to a 30–40% increase in soil organic carbon.

**B. Improvement of Soil Structure**

*Production of exopolysaccharides.*  
PGPR produce exopolysaccharides (EPS), which are high-molecular-weight polymers composed of sugars, proteins, and lipids (Naseem *et.al.,* 2018). These EPS are released into the soil matrix, enhancing soil aggregation by binding soil particles together. Improved soil aggregation increases water retention, reduces soil erosion, and promotes root penetration. Research has shown that *Bacillus subtilis* and *Pseudomonas putida* produce EPS that contributes to a 25–35% increase in soil aggregation.

*Soil aggregation.*  
Soil aggregation is essential for maintaining soil structure and fertility (Bronick *et.al.,* 2005). PGPR-induced aggregation improves soil porosity and aeration, facilitating root growth and enhancing microbial activity. Enhanced aggregation also reduces nutrient leaching and improves the availability of essential nutrients to plants. Studies indicate that EPS-producing PGPR can enhance aggregate stability by 30–40% under controlled conditions.

**C. Soil pH Modification**

*PGPR influence on rhizosphere pH.*  
PGPR can alter rhizosphere pH through various metabolic processes, including organic acid production, ammonium assimilation, and nitrogen fixation. Acidification or alkalinization of the rhizosphere affects nutrient solubility and availability. For instance, phosphate-solubilizing bacteria produce organic acids that reduce soil pH, enhancing phosphate solubilization and making it readily available to plants. Studies have shown that PGPR-induced pH reduction can increase phosphorus availability by 40–50%.

*Impact on nutrient availability.*  
Soil pH modification by PGPR influences the availability of nutrients such as phosphorus, iron, and manganese (Etesami *et.al.,* 2020). In calcareous soils, where phosphorus availability is often limited, PGPR-mediated acidification can significantly improve phosphorus solubilization and uptake by plants. Moreover, PGPR can enhance iron availability by producing siderophores, which chelate iron from the soil and make it accessible to plants.

**D. Biofertilizer Formulations and Applications**

*Types of biofertilizers (Single-strain, multi-strain, consortia).*  
Biofertilizers are classified into single-strain, multi-strain, and consortium formulations based on the type of microorganisms used (Rakshit *et.al.,* 2021). Single-strain biofertilizers contain one type of PGPR, such as *Rhizobium* or *Azospirillum*. Multi-strain formulations consist of two or more beneficial bacterial species, enhancing overall plant growth and nutrient uptake. Consortium formulations combine different microbial species with complementary functions, providing enhanced benefits such as nitrogen fixation, phosphate solubilization, and disease suppression. Consortium biofertilizers have shown a 20–30% increase in crop yields compared to single-strain applications.

*Methods of application (Seed coating, soil inoculation, foliar application).*  
PGPR-based biofertilizers can be applied through various methods, including seed coating, soil inoculation, and foliar application (Basu *et.al.,* 2021). Seed coating involves coating seeds with bacterial formulations, promoting early colonization of plant roots. Soil inoculation is achieved by applying biofertilizers directly to the soil, enhancing rhizosphere interactions. Foliar application, though less common, can improve nutrient uptake and stress resistance. Studies have reported yield improvements of 15–25% in crops treated with PGPR through these methods.

**IV. Role of PGPR in Enhancing Crop Yield**

**A. Plant Growth Promotion**

*Enhanced root and shoot growth.*  
PGPR have demonstrated significant potential to enhance root and shoot growth by synthesizing phytohormones, improving nutrient availability, and facilitating nutrient uptake (Grover *et.al.,* 2021). The production of Indole-3-acetic acid (IAA) by *Azospirillumbrasilense* and *Pseudomonas fluorescens* has been shown to stimulate root elongation and lateral root proliferation, resulting in increased nutrient absorption. Studies indicate that *Azospirillum* inoculation can enhance root biomass by approximately 30% and shoot biomass by 25% in wheat and maize.  
Reports have also demonstrated the efficacy of *Bacillus subtilis* in promoting root growth through the production of gibberellins and cytokinins (Poveda *et.al.,* 2021). Experiments involving tomato plants treated with *Bacillus subtilis* have shown a 20% increase in shoot length and a 15% increase in dry weight compared to untreated plants. Such enhancement in root and shoot growth contributes to improved plant vigor and higher crop yields.

*Improved seed germination.*  
PGPR positively influence seed germination through mechanisms such as nutrient mobilization, phytohormone production, and pathogen suppression. Studies have demonstrated that *Pseudomonas putida* enhances seed germination in cereals by up to 35% under controlled conditions.  
Research involving *Bacillus amyloliquefaciens* indicates that seed inoculation can increase germination rates by 20–30% and enhance seedling establishment under field conditions. Improved seed germination results in better crop stand establishment, which is crucial for achieving higher yields.

**B. Stress Tolerance Induction**

*Drought tolerance.*  
PGPR can enhance plant tolerance to drought stress through several mechanisms, including osmotic adjustment, antioxidant production, and the production of stress-related hormones (Gowtham *et.al.,* 2022). Studies have shown that inoculation with *Pseudomonas fluorescens* can increase drought tolerance in wheat by enhancing proline accumulation and reducing lipid peroxidation by approximately 30%.  
Reports indicate that *Azospirillumbrasilense* improves water-use efficiency by promoting root development and increasing soil moisture retention, resulting in yield improvements of 10–15% under water-limited conditions.

*Salinity tolerance.*  
PGPR contribute to enhanced salt tolerance by producing osmolytes, modulating ion transport, and inducing antioxidant enzyme activity (Ali *et.al.,* 2022). Studies involving *Bacillus subtilis* and *Pseudomonas putida* have shown that treated plants exhibit improved salt tolerance through the accumulation of compatible solutes such as proline and glycine betaine.  
Research has demonstrated that inoculation with *Pseudomonas fluorescens* enhances tomato plant growth under saline conditions by reducing sodium uptake and increasing potassium assimilation, resulting in yield improvements of 20–25%.

*Heavy metal stress mitigation.*  
PGPR contribute to heavy metal stress mitigation by producing siderophores, organic acids, and extracellular polymeric substances that chelate toxic metal ions. Research has indicated that *Pseudomonas aeruginosa* and *Bacillus thuringiensis* can enhance plant growth in cadmium-contaminated soils by reducing metal bioavailability by 40–50% .  
Studies involving *Bacillus megaterium* have demonstrated its potential to mitigate lead stress in maize by enhancing antioxidant enzyme activity and promoting root growth, leading to a yield increase of approximately 15% (Hashem *et.al.,* 2019).

**C. Biocontrol of Pathogens**

*Antibiosis and competition.*  
PGPR exhibits biocontrol activity against various phytopathogens by producing antibiotics, lytic enzymes, and secondary metabolites. *Pseudomonas fluorescens* and *Bacillus subtilis* are well-known for their ability to produce antifungal compounds such as 2,4-diacetylphloroglucinol (DAPG), pyoluteorin, and surfactin.  
Studies indicate that *Pseudomonas fluorescens* application reduced the incidence of *Fusarium* wilt in tomato plants by approximately 70% compared to untreated controls.

*Induced systemic resistance (ISR).*  
PGPR can trigger ISR in plants, enhancing their resistance against a broad spectrum of pathogens (Choudhary *et.al.,* 2007). This defense mechanism is mediated through the production of signaling molecules such as salicylic acid, jasmonic acid, and ethylene. *Bacillus subtilis* has been shown to induce ISR in tomato plants, leading to a 60–75% reduction in disease incidence caused by *Rhizoctonia solani*.  
Research has demonstrated that *Pseudomonas fluorescens* can induce ISR in rice against *Magnaporthe oryzae*, resulting in a yield increase of 15–20% under field conditions.

**D. Field Application Studies**

*Case studies of PGPR application in various crops.*  
Field studies have consistently demonstrated the effectiveness of PGPR in enhancing crop yields. In maize, *Azospirillumbrasilense* inoculation resulted in a 20–30% increase in grain yield under nitrogen-limited conditions.  
In tomato, *Pseudomonas fluorescens* application led to yield improvements of 25–35% by enhancing nutrient uptake and providing protection against *Fusarium* wilt.

*Comparative analysis with chemical fertilizers.*  
Comparative studies have shown that PGPR-based treatments can achieve yield improvements comparable to chemical fertilizers (Sedri *et.al.,* 2022). In wheat, the combined use of *Bacillus subtilis* and reduced chemical fertilizer input led to a 15% increase in yield while maintaining soil health.  
Research indicates that biofertilizer formulations combining *Azospirillum, Pseudomonas,* and *Bacillus* can replace up to 30% of nitrogen and phosphorus fertilizers without compromising crop productivity.

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**V. Challenges and Limitations**

**A. Environmental Factors**

*Soil pH, temperature, moisture content.*  
The efficiency of PGPR is significantly influenced by environmental factors such as soil pH, temperature, and moisture content (Pereira *et.al.,* 2020). Most PGPR strains demonstrate optimal growth and functionality within a pH range of 6.0 to 7.5, although some acid-tolerant strains like *Azospirillum* and *Pseudomonas* are effective at pH values as low as 5.0.  
Temperature variations also affect the survival and colonization ability of PGPR. Many strains are most effective between 20°C and 30°C, with performance declining significantly at temperatures above 35°C or below 10°C. Research has shown that *Pseudomonas fluorescens* exhibits reduced siderophore production under heat stress, thereby limiting its biocontrol potential.  
Moisture content plays a critical role in determining the efficacy of PGPR. Waterlogged soils tend to suppress aerobic bacteria such as *Bacillus* and *Pseudomonas*, while drought conditions can reduce bacterial survival and activity by up to 50%.  
These environmental factors not only affect PGPR growth but also influence their interactions with plant roots, nutrient availability, and overall effectiveness in promoting plant growth (Nadeem *et.al.,* 2014).

*Impact of soil type on PGPR effectiveness.*  
Soil type significantly influences PGPR activity by affecting nutrient availability, water retention, and microbial diversity (Zheng *et.al.,* 2018). Studies have shown that clayey soils with high organic matter content support better PGPR colonization compared to sandy soils with low organic content.  
Research indicates that phosphate-solubilizing bacteria (PSB) are more effective in acidic soils, where phosphate availability is limited, while nitrogen-fixing bacteria such as *Rhizobium* perform better in well-drained loamy soils.  
Field studies have demonstrated that the efficacy of *Bacillus subtilis* in promoting plant growth can vary by up to 40% depending on soil texture and organic matter content.

**B. Formulation and Application Challenges**

*Consistency in field performance.*  
The inconsistency of PGPR performance under field conditions compared to laboratory and greenhouse settings remains a significant limitation (Shah *et.al.,* 2021). While controlled conditions allow for optimal growth and colonization of PGPR, factors such as soil heterogeneity, microbial competition, and climatic variations can drastically reduce their effectiveness in the field.  
Studies have shown that biofertilizer treatments result in yield increases of 15–30% under laboratory conditions but only 5–15% under field conditions.  
Formulation techniques aimed at enhancing field performance, such as encapsulation and biofilm-based formulations, have shown promise, but challenges related to cost, scalability, and compatibility with existing agricultural practices remain unresolved.

*Shelf-life and viability of PGPR formulations.*  
The shelf-life and viability of PGPR-based biofertilizers are crucial factors determining their commercial success (Basu *et.al.,* 2021). Many formulations, particularly those involving free-living bacteria, have limited shelf-life due to desiccation, temperature fluctuations, and microbial contamination.  
Research indicates that the survival rate of *Azospirillum* in liquid formulations declines by 40–50% after six months of storage under ambient conditions.  
Development of carrier materials such as peat, lignite, and vermiculite has shown potential for improving shelf-life, but their use is often limited by cost and environmental concerns.

**C. Compatibility Issues**

*Interactions with native soil microbiota.*  
PGPR introduced into the soil environment often faces competition from indigenous microbial communities. Native soil microbiota can inhibit the colonization and establishment of introduced PGPR through mechanisms such as nutrient competition, antibiosis, and predation.  
Studies have demonstrated that PGPRs like *Pseudomonas fluorescens* and *Bacillus subtilis* exhibit reduced colonization efficiency in soils with high microbial diversity, with colonization rates declining by up to 30% compared to sterile or low-diversity soils.  
The presence of antagonistic microorganisms can also hinder the effectiveness of PGPR in promoting plant growth and inducing systemic resistance (Meena *et.al.,* 2020). Effective strategies are needed to improve PGPR compatibility with native soil communities.

*Crop-specific responses.*  
PGPR often exhibit varying degrees of effectiveness depending on the crop species and variety. Research has shown that *Rhizobium* strains highly effective in promoting growth in legumes may have limited effects on cereals and other non-leguminous crops.  
Crop-specific variations in root exudates, rhizosphere pH, and root architecture can influence the ability of PGPR to colonize and exert beneficial effects. Studies indicate that some PGPR strains may enhance growth in wheat by 20–30% but show no significant impact on rice under similar conditions.

**D. Regulatory and Commercialization Barriers**

*Registration procedures.*  
The commercialization of PGPR-based products faces numerous regulatory hurdles, particularly concerning registration and quality control standards (Basu *et.al.,* 2021). Different countries have established varying criteria for the approval and marketing of biofertilizers, often requiring extensive testing to demonstrate efficacy and safety.  
These regulatory procedures can be time-consuming and costly, limiting the availability of commercially viable PGPR products. Reports indicate that the approval process for new formulations can take 3–5 years, impacting their adoption by farmers.

*Acceptance by farmers and stakeholders.*  
The widespread adoption of PGPR-based biofertilizers is often hindered by factors such as lack of awareness, perceived efficacy issues, and compatibility with conventional farming practices. Surveys indicate that only 20–30% of farmers are willing to adopt biofertilizers without financial incentives or government support.  
Efforts to improve knowledge dissemination, provide subsidies, and integrate biofertilizers with existing nutrient management systems are essential for promoting their use on a broader scale.

**VI. Future Prospects and Research Directions**

**A. Molecular and Genetic Approaches**

*Genetic engineering of PGPR strains.*  
The application of genetic engineering techniques offers promising avenues for enhancing the efficacy of PGPR (Sudheer *et.al.,* 2020). By modifying genes responsible for nitrogen fixation, phosphate solubilization, phytohormone production, and stress tolerance, researchers aim to improve the efficiency and adaptability of PGPR under varying environmental conditions.  
Efforts to engineer *Pseudomonas fluorescens* have demonstrated enhanced biocontrol capabilities through the overexpression of antibiotic-producing genes such as *phlD* and *prnC*, resulting in improved suppression of *Fusarium* wilt by up to 70%.  
Recent advancements involve the use of CRISPR-Cas9 technology for genome editing of *Rhizobium* and *Azospirillum* strains to improve nitrogen fixation efficiency. Experiments have shown that genetically modified *Azospirillumbrasilense* exhibits a 30% increase in ammonia production compared to wild-type strains.  
Moreover, the development of genetically engineered PGPR strains with enhanced stress tolerance has shown potential for improving plant growth under drought and saline conditions (Lucas *et.al.,* 2023).

*Understanding PGPR-crop signaling pathways.*  
Deciphering the molecular mechanisms underlying PGPR-plant interactions is essential for improving their effectiveness. Studies have identified signalling molecules such as quorum-sensing molecules, volatile organic compounds (VOCs), and phytohormones that play critical roles in plant-microbe communication.  
Transcriptomic and proteomic analyses have provided insights into the genes and proteins involved in the colonization of plant roots by PGPR. For example, the production of VOCs like 2,3-butanediol by *Bacillus subtilis* has been shown to trigger systemic resistance in plants, enhancing their tolerance to pathogens by approximately 60%.  
Future research focusing on elucidating the signalling pathways involved in plant-PGPR interactions could lead to the development of more effective biofertilizers and biocontrol agents (Bukhat *et.al.,* 2020).

**B. Integration with Modern Agricultural Practices**

*PGPR in sustainable agriculture.*  
The application of PGPR in sustainable agriculture aims to reduce the dependence on chemical fertilizers and pesticides. Recent studies indicate that the use of PGPR as biofertilizers can reduce the requirement for nitrogen and phosphorus fertilizers by 30–40% without compromising crop yields.  
Research involving *Azospirillum, Pseudomonas,* and *Bacillus* species has demonstrated that these bacteria can enhance nutrient use efficiency, improve soil fertility, and promote plant growth under organic farming systems.  
Adopting PGPR-based technologies in sustainable agriculture could significantly reduce environmental pollution, promote soil health, and contribute to achieving food security (Shah *et.al.,* 2021).

*Combined application with organic and chemical fertilizers.*  
The co-application of PGPR with organic and chemical fertilizers offers a balanced approach to optimizing nutrient availability and promoting plant growth. Studies have shown that combining *Pseudomonas fluorescens* with reduced doses of chemical fertilizers results in yield increases of up to 25% in maize and wheat.  
Research has demonstrated that integrating PGPR with organic amendments such as compost, vermicompost, and manure can enhance microbial activity, improve soil structure, and increase nutrient availability (Song *et.al.,* 2015).  
Field trials involving consortium formulations of *Azospirillum, Rhizobium, Bacillus,* and *Pseudomonas* have demonstrated synergistic effects, resulting in yield improvements of 30–35% in cereal and legume crops.  
Future studies focusing on optimizing the dosage and application methods of PGPR combined with organic and chemical fertilizers are essential for maximizing their benefits.

**C. Development of Novel Formulations**

*Multi-strain consortia.*  
The use of multi-strain consortia consisting of different PGPR species is gaining attention due to their ability to perform complementary functions. Consortium formulations can simultaneously enhance nitrogen fixation, phosphate solubilization, phytohormone production, and disease suppression, providing a comprehensive approach to improving crop yield.  
Studies have reported that multi-strain biofertilizers can increase crop yields by 20–40% compared to single-strain formulations.  
Research focusing on developing compatible consortia and understanding their synergistic interactions is essential for enhancing their effectiveness in various cropping systems.

*Nano-formulations and smart delivery systems.*  
Nanotechnology offers novel approaches for enhancing the efficiency of PGPR through nano-formulations and smart delivery systems. Encapsulation of PGPR in nanomaterials such as chitosan, silica, and alginate beads can improve their stability, shelf-life, and colonization ability.  
Research indicates that nano-encapsulated *Azospirillum* and *Pseudomonas* formulations exhibit enhanced nutrient solubilization and plant growth-promoting activities by approximately 30–50% compared to conventional formulations.  
The development of smart delivery systems that release PGPR in response to environmental stimuli, such as pH and moisture levels, holds significant potential for improving their efficacy under field conditions (Campos *et.al.,* 2023).

**D. Policy and Awareness**

*Promoting PGPR use in developing countries.*  
The adoption of PGPR-based technologies in developing countries faces challenges related to lack of awareness, limited access to quality biofertilizers, and inadequate policy support.  
Promoting PGPR use through farmer education, subsidies, and government incentives could enhance their acceptance and contribute to improving crop productivity while reducing environmental impact.  
Collaborative research programs involving local research institutes, international organizations, and private industries could accelerate the development and dissemination of effective PGPR-based technologies.

*Encouraging collaborative research and commercialization.*  
The commercialization of PGPR products requires coordinated efforts among researchers, industries, and regulatory agencies (Sekar *et.al.,* 2016). Standardization of protocols for efficacy testing, quality control, and formulation development is essential for promoting their large-scale use.  
Establishing public-private partnerships and enhancing funding for research and development can facilitate the transition of PGPR-based technologies from laboratories to field applications.  
Developing international guidelines and harmonizing regulatory frameworks could accelerate the commercialization of biofertilizers globally.

**Conclusion**

Plant Growth-Promoting Rhizobacteria (PGPR) play a crucial role in enhancing soil fertility, promoting crop yield, and improving plant resilience to various stress conditions. By facilitating nitrogen fixation, phosphorus solubilization, hormone production, and disease suppression, PGPR offers a sustainable alternative to chemical fertilizers and pesticides. Despite their potential, challenges related to environmental factors, formulation consistency, compatibility with native microbiota, and regulatory barriers hinder their widespread adoption. Advances in genetic engineering, multi-strain consortia, and nano-formulations present promising strategies for improving PGPR efficacy. Integrating PGPR with modern agricultural practices, combined with supportive policies and awareness programs, can promote their large-scale application in sustainable agriculture. Future research should focus on developing efficient, cost-effective formulations and enhancing collaboration between researchers, policymakers, and industries to ensure global food security and environmental sustainability.

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1.

2.

3.

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