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Plant Growth Promoting Rhizobacteria for Sustainable Agriculture

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ABSTRACT

Beneficial soil microorganisms known as plant growth-promoting rhizobacteria (PGPR) increase plant production and growth through a variety of direct and indirect processes. By fixing nitrogen, solubilizing phosphate, and producing phytohormones, they increase the availability of nutrients. They also shield plants against infections by producing siderophores, antibiotics, and systemic resistance. Additionally, PGPR makes plants more resilient to abiotic challenges such salt, drought, and heavy metal toxicity. Their use lessens reliance on chemical pesticides and fertilizers, encouraging sustainable and ecologically friendly farming. This review focuses on PGPR's methods, agricultural applications, advantages, difficulties, and prospects for enhancing global food security.

KEYWORDS
Plant growth-promoting rhizobacteria (PGPR), sustainable agriculture, biofertilizers, rhizosphere, plant growth promotion, biological nitrogen fixation, phosphate solubilization, phytohormone production, biocontrol, abiotic stress tolerance, soil health, and crop productivity.

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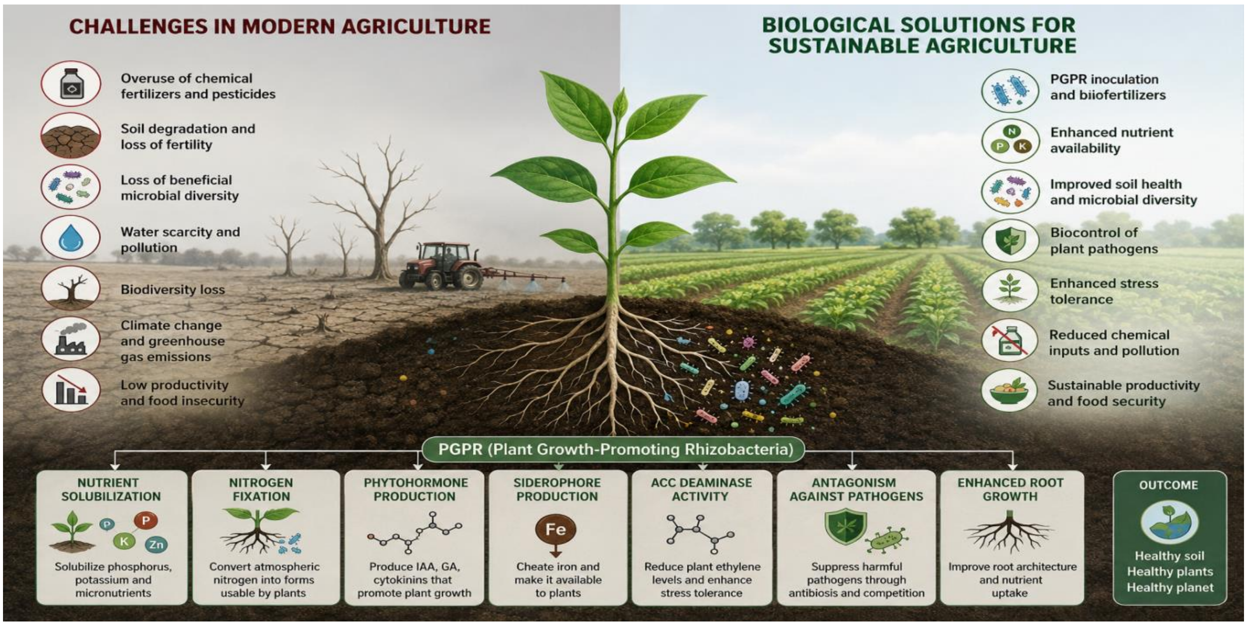
1. Introduction

Sustainable Agriculture: Worldwide Issues and the Requirement for Biological Remedies
The foundation of global food security is agriculture, which sustains the dietary needs of a constantly expanding human population while making a substantial contribution to rural livelihoods and economic growth. The Food and Agriculture Organization (FAO) estimates that in order to feed the world's expected 9.7 billion people by 2050, food production must rise by over 60–70% (FAO, 2022; United Nations, 2022). However, decreasing soil fertility, climate change, water scarcity, environmental pollution, biodiversity loss, and overuse of synthetic fertilizers and pesticides have made reaching this goal more challenging (Tilman et al., 2002; Lal, 2015; Pretty, 2008).

By using chemical fertilizers, insecticides, irrigation, and high-yielding crop types, the Green Revolution greatly enhanced agricultural production. Despite the fact that these technologies improved food production, their indiscriminate and long-term use has had detrimental effects on the environment, including reduced microbial diversity, soil degradation, nutrient imbalance, groundwater contamination, and greenhouse gas emissions (Foley et al., 2011; Lal, 2015). Long-term agricultural sustainability is at risk due to the constant use of chemical fertilizers, which has changed the physicochemical characteristics of the soil, decreased soil organic matter, and decreased beneficial microbial populations (Bhardwaj et al., 2014; Backer et al., 2018).

Therefore, boosting crop output while preserving natural resources and reducing environmental harm is a dual problem facing modern agriculture. In order to maintain productivity without sacrificing environmental quality or future food security, sustainable agriculture has arisen as a comprehensive strategy that combines ecological concepts with agricultural methods (Pretty, 2008; FAO, 2022). Effective nutrient management, biodiversity conservation, chemical input reduction, and the encouragement of naturally occurring biological processes that support robust crop growth are all key components of sustainable farming (Lal, 2015).

Because beneficial soil microorganisms can naturally improve plant nutrition, increase stress tolerance, and reduce plant diseases, they have garnered significant scientific attention among the diverse biological techniques established in recent decades. Because they enhance crop performance while lowering reliance on chemical fertilizers and pesticides, microbial inoculants have emerged as crucial elements of environmentally friendly farming systems (Vessey, 2003; Bhattacharyya & Jha, 2012). Because of their many uses in promoting soil fertility and plant health, Plant Growth-Promoting Rhizobacteria (PGPR) are regarded as one of the most promising biological tools for sustainable agriculture (Backer et al., 2018; Olanrewaju et al., 2017).



Rhizosphere: A Plant-Microbe Interaction Hotspot

One of the most biologically active areas of terrestrial ecosystems is the rhizosphere, which is the small area of soil directly impacted by plant roots. Root exudates are a variety of organic molecules that are continuously released by plant roots, including sugars, proteins, amino acids, organic acids, vitamins, flavonoids, and secondary metabolites. For the various microbial communities that live in the rhizosphere, these substances act as signaling molecules and energy sources (Lugtenberg & Kamilova, 2009; Philippot et al., 2013).

Actinomycetes, algae, bacteria, fungi, archaea, and protozoa all interact dynamically with plant roots in the rhizosphere. Depending on the microbial species involved and the surrounding circumstances, these interactions could be advantageous, neutral, or harmful. While pathogenic microorganisms may hinder plant growth and agricultural output, beneficial microbes increase nutrient availability, promote root growth, shield plants from pathogens, and improve tolerance to environmental stresses (Berendsen et al., 2012; Philippot et al., 2013).

Rhizosphere microbial communities are far more diverse and functionally complicated than previously thought, according to recent developments in metagenomics, next-generation sequencing, and microbial ecology. Plant genotype, soil properties, climate, agricultural management techniques, and environmental stressors all affect the makeup of these microbial communities (Compant et al., 2019). Soil fertility, nutrient cycling, carbon sequestration, disease prevention, and ecosystem resilience are all greatly aided by robust rhizosphere microbial populations (Finkel et al., 2017).

PGPR hold a special place in these intricate microbial populations due to their capacity to form advantageous relationships with plant roots while concurrently enhancing plant growth via a variety of physiological and biochemical processes (Bhattacharyya & Jha, 2012). They are useful biofertilizers and biostimulants for sustainable crop development due to their ability to effectively colonize the rhizosphere.

Definition, Background, and Diversity of Plant Growth-Promoting Rhizobacteria (PGPR)

Kloepper and Schroth (1978) established the idea of Plant development-Promoting Rhizobacteria, characterizing these bacteria as free-living soil microorganisms that can colonize plant roots and promote plant development. Since then, PGPR has grown to be one of the beneficial microbe families in agricultural microbiology that has been investigated the most.

Pseudomonas, Bacillus, Azospirillum, Azotobacter, Rhizobium, Paenibacillus, Enterobacter, Serratia, Burkholderia, Arthrobacter, and Streptomyces are among the phylogenetically varied collection of bacteria that make up PGPR (Glick, 2012; Lugtenberg & Kamilova, 2009). According to Compant et al. (2005), these bacteria can live freely in soil, colonize the rhizoplane, or live as endophytes inside plant tissues.

Because of their diversity, PGPR may carry out a wide range of ecological tasks that either directly or indirectly affect plant growth. In addition to generating phytohormones that control plant growth, they enhance nutrient uptake through biological nitrogen fixation, phosphate solubilization, potassium mobilization, and micronutrient availability (Vessey, 2003; Rodríguez & Fraga, 1999). Furthermore, a large number of PGPR generate hydrogen cyanide, lytic enzymes, antibacterial chemicals, siderophores, and volatile organic compounds that inhibit plant pathogens and lower disease incidence (Lugtenberg & Kamilova, 2009; Pieterse et al., 2014).

PGPR's versatility sets them apart from traditional fertilizers since they support both plant nutrition and the general health of ecosystems. PGPR enhances soil biological activity, increases microbial diversity, and supports long-term soil sustainability in contrast to chemical fertilizers, which only supply nutrients (Backer et al., 2018). As a result, PGPR-based biofertilizers have drawn a lot of interest as eco-friendly substitutes that can lower fertilizer inputs while preserving or increasing crop output (Adesemoye et al., 2009).

Additionally, we now have a better understanding of PGPR-plant interactions at the cellular and molecular levels thanks to recent advances in molecular biology, genomics, transcriptomics, and proteomics. These cutting-edge methods have made it easier to create more effective microbial inoculants for sustainable agriculture by identifying a number of genes related to root colonization, stress tolerance, nutrient metabolism, and signal transduction (Compant et al., 2019; Backer et al., 2018).

Rhizobacteria's Mechanisms of Promoting Plant Growth

Through a variety of direct and indirect methods that improve nutrient uptake, control plant metabolism, and shield crops from biotic and abiotic challenges, Plant Growth-Promoting Rhizobacteria (PGPR) promote plant growth. PGPR can build a mutually beneficial relationship with plants and greatly increase agricultural productivity because both processes frequently function simultaneously (Glick, 2012; Bhattacharyya & Jha, 2012). Bacterial species, plant genotype, soil characteristics, climate, and agricultural management techniques all affect how effective PGPR is (Backer et al., 2018).

1. Biological Nitrogen Fixation

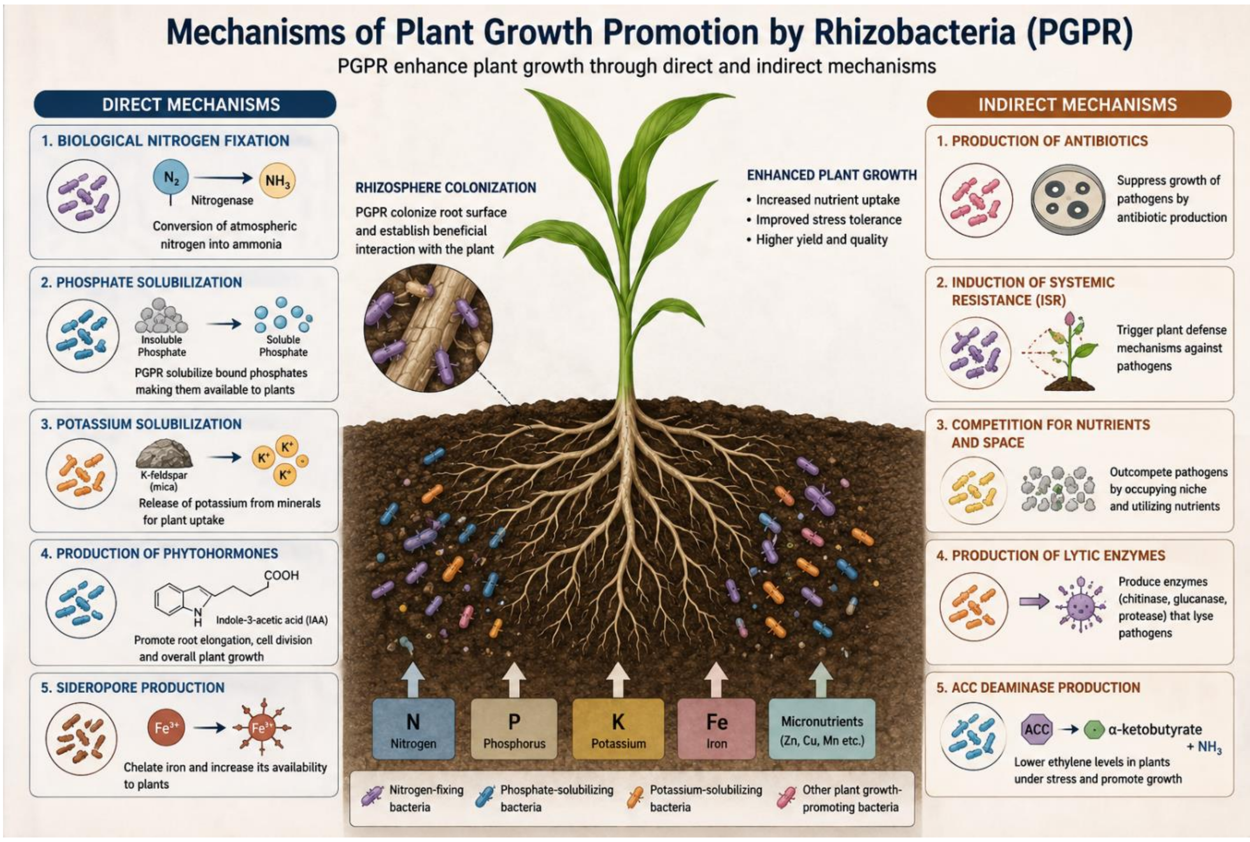
Although most plants cannot directly utilize atmospheric nitrogen (N_2), nitrogen is one of the most important macronutrients needed for plant growth. Through the nitrogenase enzyme complex, biological nitrogen fixation carried out by diazotrophic PGPR transforms atmospheric nitrogen into ammonia, making nitrogen accessible for plant uptake (Vessey, 2003). In both legumes and non-leguminous crops, genera like Rhizobium, Azospirillum, Azotobacter, Herbaspirillum, and Gluconacetobacter play an important role in biological nitrogen fixation (Hungria et al., 2010; Glick, 2012).

Utilizing nitrogen-fixing PGPR lowers production costs, lessens reliance on artificial nitrogen fertilizers, and reduces greenhouse gas emissions and nitrate leaching-related environmental pollution (Ladha et al., 2016).Inoculation with nitrogen-fixing bacteria has been shown in numerous studies to increase plant biomass, chlorophyll content, grain production, and nitrogen-use efficiency in field settings (Bhattacharyya & Jha, 2012).

2. Phosphate Solubilization and Nutrient Mobilization

Even though agricultural soils are rich in phosphorus, a significant amount of it is present in insoluble mineral complexes that plant roots are unable to absorb. Insoluble phosphates are dissolved into plant-available forms by phosphate-solubilizing PGPR, which releases organic acids such gluconic acid, citric acid, oxalic acid, and malic acid (Rodríguez & Fraga, 1999; Sharma et al., 2013). These bacteria also create phosphatase enzymes, which mineralize organic phosphorus molecules.

Through acidification, chelation, and enzymatic processes, a number of PGPR mobilize micronutrients such as potassium, zinc, iron, and phosphorus (Richardson et al., 2009). Increased nutrient availability promotes photosynthesis, protein synthesis, root development, and general plant growth.
According to Adesemoye et al. (2009), PGPR's integrated nutrient-mobilizing capacity minimizes excessive fertilizer input while enhancing soil fertility and sustainable nutrient management.



3. Manufacturing of Regulators of Plant Growth

The capacity of PGPR to produce phytohormones that directly affect plant growth and development is one of its unique traits. Gibberellins, cytokinins, ethylene-modulating enzymes, abscisic acid, and indole-3-acetic acid (IAA) are some of these hormones (Spaepen et al., 2007). Because it promotes root elongation, lateral root formation, and root hair production, increasing the surface area accessible for nutrition and water absorption, indole-3-acetic acid is the bacterial phytohormone that has been investigated the most (Patten & Glick, 2002). Improved root architecture increases nitrogen uptake in nutrient-deficient environments and allows plants to explore more soil volumes.
Gibberellins and cytokinins, which control seed germination, cell division, flowering, fruit development, and biomass accumulation, are also produced by a number of PGPR (Egamberdieva et al., 2017). In both normal and stressful conditions, these hormonal interactions greatly increase crop productivity.

4. Stress Reduction and ACC Deaminase Activity

Drought, salinity, flooding, heavy metals, and severe temperatures are examples of environmental conditions that cause plants to produce excessive amounts of ethylene. Elevated ethylene levels limit photosynthesis, prevent root elongation, and stunt plant growth (Glick, 2014). The enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which breaks down ACC, the direct precursor of ethylene, is produced by several PGPR. Reduced ethylene concentrations lessen the growth

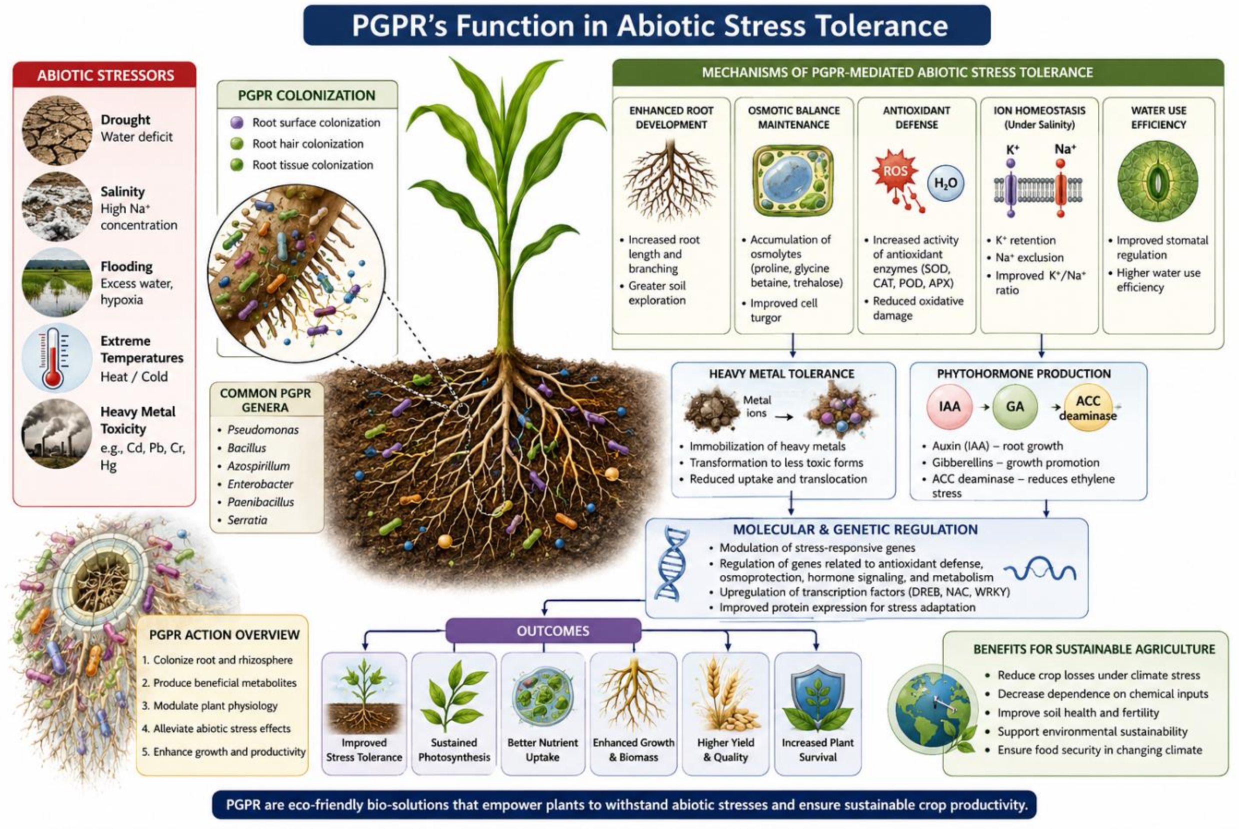
inhibition brought on by stress and enable plants to continue their regular physiological processes in challenging environmental circumstances (Nascimento et al., 2020).
In many crops, such as wheat, maize, rice, soybean, tomato, and chickpea, ACC deaminase-producing bacteria have been shown to improve drought tolerance, salinity resistance, and heavy metal tolerance (Glick, 2014; Olanrewaju et al., 2017).

5. Biological Management of Plant Illnesses

Global agricultural output has significantly decreased as a result of plant diseases brought on by bacteria, viruses, nematodes, and fungi. Overuse of chemical pesticides has resulted in disease resistance, environmental contamination, and detrimental impacts on beneficial organisms (Pieterse et al., 2014).
Through a variety of ways, PGPR serve as efficient biological control agents. Numerous bacterial species produce antibiotics that prevent the growth of pathogenic germs, including phenazines, pyrrolnitrin, 2,4-diacetylphloroglucinol, and cyclic lipopeptides (Lugtenberg & Kamilova, 2009). Chitinases, glucanases, cellulases, and proteases are among the hydrolytic enzymes produced by other PGPR that break down fungal cell walls and inhibit the growth of pathogens (Compant et al., 2005).
PGPR compete with pathogens in the rhizosphere for nutrients and ecological niches in addition to direct hostility. While providing iron to plants, siderophore-producing bacteria chelate iron from the surrounding soil, reducing the amount of iron available to harmful microorganisms (Neilands, 1995).
Induced Systemic Resistance (ISR), in which PGPR activates the plant immune system prior to pathogen invasion, is another crucial defense mechanism. Plants are able to react quickly to pathogen invasion because ISR increases the synthesis of defense-related proteins, phenolic compounds, antioxidant enzymes, and signaling molecules (Pieterse et al., 2014; Berendsen et al., 2012).
These combined methods allow PGPR to minimize the usage of chemical pesticides and fungicides while reducing the incidence of disease.

6. PGPR's Function in Abiotic Stress Tolerance

Abiotic stressors like drought, salt, flooding, severe temperatures, and heavy metal contamination have all been made worse by climate change and have a negative impact on crop productivity globally (IPCC, 2023). Thus, creating agricultural systems that are adaptable to climate change has emerged as a top research goal.



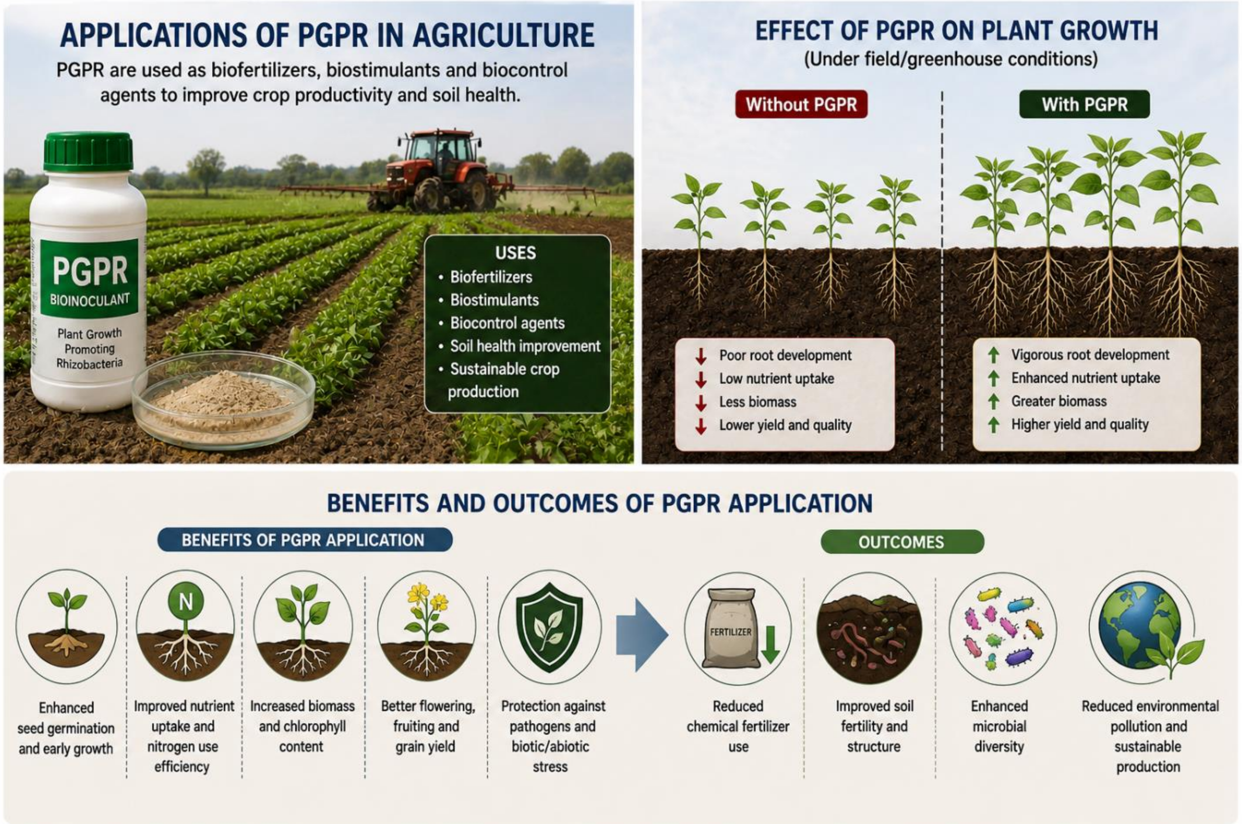
Through a number of physiological and biochemical processes, PGPR increases plant resistance to abiotic stress. They increase the activity of antioxidant enzymes, control osmotic balance by accumulating osmolytes, preserve chlorophyll content, enhance water-use efficiency, and promote root growth under stressful situations (Olanrewaju et al., 2017; Backer et al., 2018).

PGPR increases the length and branching of roots during droughts, enabling plants to access deeper soil moisture. They control potassium and sodium ion homeostasis during salinity stress while lowering oxidative damage brought on by reactive oxygen species (Egamberdieva et al., 2017). Additionally, certain bacterial strains protect plants from metal toxicity by immobilizing poisonous heavy metals or changing them into less dangerous forms (Ma et al., 2016). Moreover, PGPR affects the expression of stress-responsive genes related to cellular metabolism, hormone signaling, antioxidant defense, and osmoprotection. PGPR-mediated gene regulation is crucial for enhancing plant adaptation to shifting environmental conditions, according to developments in transcriptome and proteomic investigations (Compant et al., 2019).

7. Applications of PGPR in Agriculture

Over the past 20 years, the use of PGPR in agriculture has grown significantly as a result of the growing demand for ecologically friendly farming methods. For cereals, legumes, vegetables, fruits, oilseed crops, and horticultural plants, PGPR are increasingly frequently developed as biofertilizers, biostimulants, and biocontrol agents (Backer et al., 2018).

Under both greenhouse and field circumstances, commercial PGPR inoculants have shown notable advantages in seed germination, nitrogen uptake, chlorophyll concentration, biomass accumulation, flowering, fruit production, and grain quality (Vessey, 2003; Adesemoye et al., 2009). Reduced fertilizer use, increased soil fertility, increased microbial diversity, and decreased environmental pollution are all supported by their incorporation into sustainable agricultural systems.



Conclusion

By boosting nutrient availability, promoting plant growth, inhibiting pathogens, and boosting resistance to environmental stresses, Plant Growth-Promoting Rhizobacteria (PGPR) provide a sustainable and environmentally acceptable way to increase agricultural production. Their use can support soil health and environmental preservation while lowering reliance on chemical pesticides and fertilizers. In order to achieve climate-resilient, sustainable agriculture and guarantee long-term global food security, more research, technological developments, and successful commercialization of PGPR-based biofertilizers will be essential.

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