Inventum Biologicum: *An International Journal of Biological Research*
2024, Vol. 4, Issue 4, pp. 126-135

Inventum Biologicum

Journal homepage: www.journals.worldbiologica.com/ib

Review paper

PGPR: A Plant Growth Enhancer in Sustainable Agriculture

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ARTICLE INFO

Keywords

PGPR
Crop production
Plant nutrition
Soil fertility
Sustainable agriculture

DOI
10.5281/ib-1241224

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ABSTRACT

Plant growth-promoting rhizobacteria (PGPR) are beneficial microorganisms that live in the rhizosphere of plants and play an important role in their growth and development. The importance of PGPR for long-term agricultural viability is discussed in this review. Some plant growth mechanisms are nitrogen fixation, phosphate solubilization, and hormone secretion. PGPR's potential benefits include increased plant tolerance to biotic and abiotic stress, reduced chemical fertilizers and pesticide usage, and improved nutrient availability, soil fertility, and absorption. PGPR has various ecological and practical purposes in the soil rhizosphere. PGPR plays a key function in agroecosystems by increasing the synthesis of phytohormones and metabolites, which directly affect plant growth. Phytopathogens can be stopped in their tracks, a plant's natural defenses strengthened, and so on. The PGPR performs a variety of tasks, including the synthesis of indole acetic acid (IAA), ammonia (NH_3), hydrogen cyanide (HCN), and catalase. In addition to promoting nutrient uptake, PGPR regulates hormone production that boosts root size and strength. PGPR for sustainable agriculture offers numerous ecological and economic benefits, including increased crop production, reduced environmental pollution, and improved food security.

1. Introduction

In the 21st century, the global agricultural system faces challenges such as decreased productivity and ecosystem sustainability (Edward Paice, 2022). The United Nations predicts that the global population will reach 9.7 billion by 2050, leading to increased food consumption and limited supplies (United Nations. 2019; Kumar et al., 2017). Climate change has led to severe production losses in major cereal crops, resulting in yield drops of 3.8 and 5% for corn and wheat, respectively (Lipper et al., 2014). As global temperatures rise, abiotic variables emerge that negatively affect agricultural output (Pareek et al., 2020). Harmful abiotic environmental variables like salt are transforming fertile land into barren land. Salinity has a significant impact on the growth and metabolism of plants, altering physiology, biochemistry, and morphology (Gupta and Huang, 2014). Drought is projected to affect arable land above 50% by 2050 due to drastic climate change (Osakabe et al., 2014). Drought impacts photosynthetic integration, crop hydration, and supplement usage (Osakabe et al., 2014). Heavy metal contamination, while necessary for plant metabolism, can impair microbiological and phytological networks at high levels. Food is essential for survival and promotes individual and community growth. Reduced crop production is a major source of concern. The expanding population of agriculture has led to the extensive use of chemical inputs such as herbicides, fertilizers, and insecticides to increase food production. Agrochemical discharge from this land negatively impacts life on Earth due to bioaccumulation and biomagnification processes. Using insecticides to treat plant diseases might harm beneficial insects, microbiota, and soil fertility (Khatoon et al., 2020). Harmful farming systems do not ensure a sustainable future. Sustainable agriculture aims to provide social benefits and long-term environmental benefits. Sustainable farming practices are vital for satisfying global economic needs by reducing the use of pesticides and fertilizers and enhancing soil quality and plant health (De Andrade et al., 2023). Sustainable agriculture requires preserving soil variety to ensure global environmental health and food security for future generations (Kumar et al., 2017). Using eco-friendly alternatives, such as beneficial microbes, can help alleviate environmental stress. Crop benefits include nitrogen fixation, phosphate breakdown, heavy metal removal, phytohormone production (e.g., auxin, gibberellins, cytokinin), crop residue breakdown, and phytopathogen prevention (10). A study (Calvo et al., 2014) found that PGPRs improve plant health and development without emitting toxic byproducts into the environment. *Actinobacteria* is the largest genus and *Streptomyces*, with more than 500 species (Mohammadipanah and Dehhaghi, 2017). PGPR is necessary for crop production to enhance the availability of plant nutrients. PGPR can impact plant growth indirectly or directly through root colonization (Hassanisaadi et al., 2021). PGPR improves plant development by bioremediating damaged soils by removing harmful heavy metals and degrading pesticides. They mobilize nutrients, synthesize plant growth regulators, regulate phytopathogens, and improve soil quality (Backer et al., 2021). PGPRs can efficiently prevent plant diseases caused by bacteria and fungi. The phytomicrobiome, a group of beneficial microorganisms, enhances plant resilience to stress and increases agricultural productivity. PGPR, helps plants respond to biotic stress by creating chemical messengers, increasing food uptake, and releasing antibiotics (Lyu et al., 2021).

2. Advantages of Rhizobial Partnerships for Plant Development

Soil-inoculated plants with competing microorganisms can reintroduce 2-5% of rhizobacteria, known as PGPR, which can significantly affect plant development. Plants in nature have a dynamic and continual social network and do not exist alone. Microorganisms around the plant arrange and uphold the colony (Kloepper et al., 1992). Beneficial bacteria are found in the soil's rhizosphere, located around plant roots. Plants benefit from these bacteria's cooperative interaction, which promotes growth (Saravanan et al., 2011). Including eukaryotes, microbiome interactions occur in all multicellular organisms. These interactions may have occurred before plants settled in the zone. Soil is home to several microorganisms, the most common being bacteria. The rhizosphere, where plant roots and soil bacteria interact, is typically rich in microbes. Beneficial bacteria can exist freely in the soil or have symbiotic connections with plants. They can be found near or within the plant (VanPeer and Schippers, 1989). The rhizosphere is home to a diverse range of living organisms. Lazarovits (1997) found that root system processes, such as respiration and root secretion, affect the rhizosphere in both quantitative and qualitative ways. According to Miao et al. (2014), these existed before plants arrived in the region. These interactions may have a significant impact on plant development and output. When several microflorae of PGPR can colonize all ecological niches during development and crop yield.

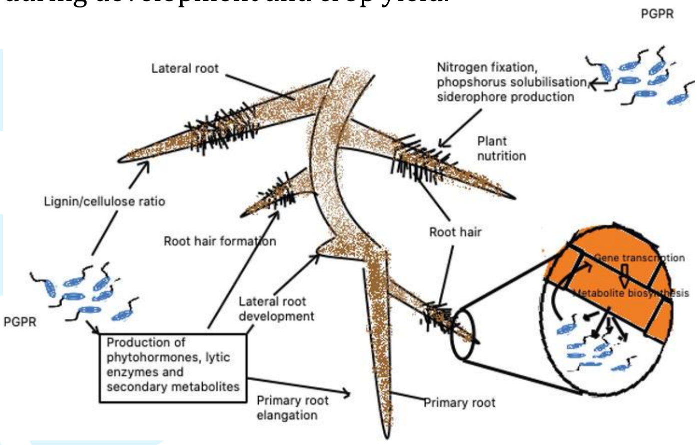

Fig. 1 Based on Vacheon's studies, the mechanisms of action that PGPR uses to encourage greater plant development (Vacheron et al., 2013)

The activities of rhizospheric bacteria are influenced by age, growth stage, plant species, soli tissue, and ecological conditions. Because of their rapid development and flexibility, bacteria can absorb nitrogen and carbon from the majority of the rhizosphere's microbial community. Some PGPRs can produce antimicrobial compounds that prevent the development of plant pathogens, protecting the plant from disease, as seen in Figure 1 (Miao et al., 2014). Scientists have studied PGPR, a naturally occurring soil bacterium, in great detail, which improves plant vigor and productivity. Plants not only benefit from protection from diseases and severe environments, but also from increased nutrient availability, growth, and root development (VanPeer and Schippers, 1989). Plants benefit from PGPR through multiple methods. PGPR can produce auxins, gibberellins, and cytokinins, which promote shoot and root growth (VanPeer and Schippers, 1989). PGPRs may easily fix unusable atmospheric N_2 into usable form supplementing the plant's nitrogen requirements. PGPRs help plants access phosphorus and other minerals by solubilizing them. PGPR colonizes the rhizosphere, competing with harmful bacteria for oxygen, space, and food. This reduces pathogen invasion and improves overall plant health. PGPR enhances plant resilience and tolerance to several environmental conditions, such as salinity, dryness, and high heat. Soil contains a diverse range of bacteria. PGPR is gaining popularity as a bio-fertilizer and insecticide in sustainable agriculture. Using fertilizers and chemical pesticides in agriculture can harm human health, and agricultural sustainability (Liu et al., 2006). Environmentally friendly and sustainable approaches are crucial for optimizing plant development and agricultural productivity. Recently, PGPR has gained popularity as a sustainable farming method (Gupta et al., 2015). PGPR is a viable strategy for promoting plant development, increasing crop output, and mitigating the ecological impact of agricultural activities while considering all aspects. This paper explores the processes and applications of PGPR in plant interactions and microbial, including sustainable agriculture.

3. Plant Growth-Promoting Mechanism

Rhizosphere microorganisms support plant growth through several techniques, Figure 2 illustrates the interactions between plants and PGPR (Shah et al., 2021). PGPR makes the following key contributions to environmentally responsible farming: PGPR can stimulate plant development through both direct and indirect ways.

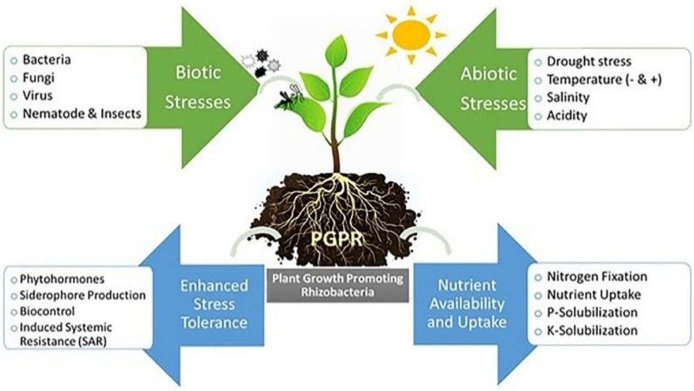

Fig. 2 Perspectives on rhizosphere-based plant-PGPR interactions (Shah et al., 2021)

3.1 Direct Mechanism

By mineralizing organic compounds, fixing nitrogen, generating phytohormones, and solubilizing mineral nutrients, PGPR can directly aid the growth and development of plants via mechanisms such as nutrient intake or greater nutrition access (Shah et al., 2021).

3.1.1 Nitrogen Fixation

Nitrogen (N) plays a critical role in plant biochemical processes, including protein synthesis and photosynthesis (Alori et al., 2017). Dinitrogen, which makes up 79% of the nitrogen in the atmosphere, has a low degree of reactivity and a triplet covalent bond, thus plants cannot use it directly. Nitrogen fertilizers, the most effective nitrogen supply technique, are now a crucial part of agricultural practices and crop production. However, their disproportionate and chronic use pollutes the environment, resulting in eutrophication, lethal releases into the environment, and harmful deposition in groundwater and other bodies of water, all of which contribute to climate change, either indirectly or directly. Bouchet et al. (2016) found that cropping systems only collect 50% of the applied nitrogen, with the remaining half escaping by leaching, volatilization, or runoff or remaining in the soil as organic complexes, accounting for around 98% of the total of soil nitrogen quantity. Unlike free-living nitrogen fixers and host plants, symbiotic nitrogen-fixing organisms have a mutually beneficial relationship with their host. Symbiotic nitrogen fixers include *Rhizobium, Mesorhizobium, Azoarcus, Burkholeria, Frankia,* and several *Achromobacter* strains (Babalola, 2010; Pérez-Montaño et al., 2014). Several bacterial taxa as nitrogen-fixing PGPRs can considerably increase plant growth (Moura et al., 2018). Nitrogenase is an energy-demanding and highly conserved enzyme that fixes nitrogen. It typically consists of two metalloprotein subunits. Bacteria must use significant energy to transform air nitrogen into usable forms. Photoautotrophs produce their carbohydrates, but nitrogen fixers rely on other species for sustenance. Legumes account for 80% of nitrogen fixed annually through symbiotic nitrogen fixation. Each legume fixes 20–200 kilograms of nitrogen each year. About 50% of the nitrogen fixed each year comes from industrial nitrogen fixation for fertilizer production (Hillel, 2008). Over 70% of legumes have mutualistic connections with rhizobia and can fix up to 200 kg of nitrogen/square meter. Legumes use symbiotic bacteria to fix nitrogen from the atmosphere, lowering the requirement for extra nitrogen until N-fertilizers are supplied. Using the given fertilizer requires less energy than atmospheric N_2 repair, leading to reduced or stopped nitrogen fixation. Spraying biological nitrogen-fixing PGPR on crops and fields promotes growth, prevents disease, and stabilizes soil nitrogen levels for farming.

3.1.2 The Dissolution of Phosphorus

Phosphorus is the 2nd most important component for plants. It is essential for respiration, signal transduction, photosynthesis, energy transmission, and macromolecular biosynthesis (Hillel, 2008).

Because 99% of the available phosphorus is precipitated or immobilized, rendering it insoluble in water, plants have difficulty absorbing it. According to Anand et al., (2016) phosphorus's weak solubility and its affinity for organic components and the soil matrix account for only 0.1% of the total P concentration in soil and plants. Plants only take phosphorus as monobasic (H_2PO_4) and dibasic $(HPO_4)^{2-}$ ions (Khan et al., 2009). In order to remedy phosphate deficits, phosphorus-based fertilizers are applied to the soil, which enables plants to rapidly access the P already present in the substrate. Supplementing commercial fertilizer with P can be costly and ineffective for vegetation due to soil loss, contamination of nearby waterways, and negative impact on ecosystems (Adesemoye and Kloepper, 2009). Beneficial microorganisms, including bacteria, fungi, and plant roots, can break down phosphorus in soil that would otherwise be intractable. According to Bechtaoui et al. (2020), PSB requires 25% less P. According to Khan et al. (2009), combining PSB with other PGPRs increases its influence. *Mesomerhizobium mediterraneum* and *Mesomerhizobium ciceri* isolated from chickpea nodules (Parmar and Sindhu, 2013), are phosphate-solubilizing bacteria. Although these bacteria increase soil fertility by solubilizing phosphorus, little research has been conducted on their potential use as biofertilizers. Phosphorus' poor solubility can limit its availability in soil (Archana et al., 2012). Some PGPRs have the unique ability to break down the soil's insoluble phosphorus molecules to increase plant accessibility.

3.1.3 The Dissolution of Potassium

Potassium (K) is the 3rd important component that plants require. Soil often has low soluble potassium content due to the presence of mineral silicates and insoluble rocks accounting for over 90%. Potassium deficiency drastically reduces crop productivity. With insufficient potassium, plants develop fewer seeds, grow slower, and yield less crop. Microorganisms, including bacteria and fungi, can interact with plants and dissolve K in soil (Setiawati and Mutmainnah, 2016). Researchers have extensively explored PGPR's ability to create and secrete organic acids capable of dissolving potassium pebbles. Some PGPRs, including *Bacillus edaphicus, Acidothiobacillus* sp., *Bacillus mucilaginosus, Burkholderia, Pseudomonas* sp., and *Ferrooxidans* sp., can dissolve potassium (Prajapati et al., 2013). Researchers discovered that *Paenibacillus* sp. converts potassium in soils from unavailable mineral forms. Research on plant PGPM shows that K-solubilizing microbes produce organic acids that increase potassium availability, promoting plant development. Soil microorganisms produce organic acids such as acid citrate, oxalate, acetate, coumaric acid, and ferulic acid, which contribute to the rhizospheric acidity. This increases the rate of mineral dissolution and proton generation, leading to the solubility of K. Scientists believe that PGPM, like PSB, can be an effective organic fertilizer that improves plant nutrient availability and reduces the need for artificial fertilizers (Khan et al., 2019).

3.1.4 Producing Siderophore

Bacteria create siderophores, tiny chemical molecules that improve iron absorption in low-iron environments. Iron is required for photosynthesis-based organisms as an enzyme cofactor in many metabolic activities such as amino acid synthesis, photosynthesis, nitrogen fixation, and oxygen transfer respiration (Tian et al., 2009). Iron is commonly found in two oxidative states: Fe^{2+} and Fe^{3+}. Plants have restricted access to the latter stage due to the development of insoluble hydroxides and iron oxides (Khoshru et al., 2020). Some PGPBs create low-molecular-weight compounds (400-1500 Da) capable of extracting iron from soil (Shanmugaiah et al., 2015). Siderophores are molecules that bind to iron and improve its bioavailability in plants (Goswami et al., 2016). Scientists have investigated microorganisms from both maritime and land habitats to determine their ability to create siderophores (Rezanka et al., 2018). Siderophores have four main chemical structures: hydroxamates, phenolates, carboxylates and pyoverdines. *Enterobacter* and *Pseudomonas* are the principal Gram-negative bacteria responsible for producing siderophores. Just 2% of organisms that are Gram-positive, such as *Bacillus* and *Rhodococcus*, can perform the same function (Czarnes et al., 2020). Good microorganisms in soil and plants produce siderophores, which compete with damaging plant diseases for iron resources and prevent them from obtaining them (Khoshru et al., 2020).

3.1.5 Solubilization of Zinc

Zinc (Zn) is an essential element for plant growth and development, with concentrations ranging from 5 to 100 mg/kg (Goteti et al., 2013). Zn is required for several physiological activities in plants, including chlorophyll formation, glucose metabolism, auxin, protein, lipid, and nucleic acid biosynthesis (Vaid et al., 2014). It also helps plants survive in new climate conditions, such as high heat and droughts (Umair Hassan et al., 2020). Zinc shortage affects almost 50% of global soils, primarily due to its association with mineral forms that plants cannot access, such as zinc silicates, zincite, zinc sulfide, and willemite, (FAO, 2002 Lopes et al., 2021). Using inorganic fertilizers to address a zinc deficit can be harmful to the environment and make a major amount of fertilizer unavailable to plants. PGPR is preferred as it may fill cation-containing minerals in nature (Kamran et al., 2017). Bacteria and fungi can saturate zinc in its insoluble form in the rhizosphere, increasing its availability. Numerous investigations have shown that Zn-mobilizing PGPR greatly increases cereal crop yields, including wheat, maize, and rice (Lopes et al., 2021). As the world's population grows, so does the demand for basic foods, leading to a rise in pesticide and fertilizer consumption. However, this could negatively harm the environment. Biofertilizers may not completely replace mineral fertilizers, but using pesticides and synthetic fertilizers to increase crop yields is crucial for feeding the world's growing population.

3.2 Indirect Mechanism

PGPR protects plants from phytopathogens by generating compounds that increase the host's natural resistance. PGPR is responsible for producing hydrolytic enzymes (e.g., chitinases, cellulases), in reaction to disease resistance or plant infections, antibiotics protecting the plant from pests, and producing VOCs and exudates through Photosynthesis, among other functions.

3.2.1 Stress Management

Stress is defined as anything that inhibits plant growth. Numerous stresses on plant growth caused by the soil environment are a significant barrier to long-term agricultural productivity. These pressures can be classified as either biotic or abiotic. Abiotic stress is the main factor responsible for about 30% of crop losses worldwide. High temperatures, salinity, and dryness can cause drought or aridity stress, which is the primary abiotic stress that impacts plant development and productivity (Vejan et al., 2016). The function of PGPR in shielding plants from environmental stressors has been thoroughly investigated by researchers using strains of microorganisms such as *Pseudomonas fluorescens* and *Pseudomonas putida*. These strains have the ability to extract cadmium ions from the ground and have a major impact on water salinity and other abiotic stressors (Baharlouei et al., 2011). Pathogens such as viruses, bacteria, fungi, protists, nematodes, insects, and viroids can cause biotic stress, resulting in decreased agricultural output (Haggag et al., 2015). Biotic stress impacts plant health in greenhouses, natural habitats, nitrogen cycling in ecosystems, and other horticultural difficulties.

3.2.2 Production of Hydrolytic Enzymes

PGPR produces protective enzymes, defining its role as a biopesticide. PGPR inhibits phytopathogenic agents, promoting plant development and producing antibiosis and antifungal chemicals for defense. Hydrolyzing enzymes produced during the process include chitinase and glucanase. Since chitinases and beta-glucanases comprise the majority of a fungal cell wall, bacteria that produce these enzymes can inhibit fungal growth. *Pseudomonas fluorescens* LPK2 and *Sinorhizobiumfredii* KCC5 produce chitinase and beta-glucanase, preventing *Fusarium udum* from causing plant wilt (Kumar et al., 2010).

3.2.3 VOCs Formation

The synthesis of volatile organic compounds (VOCs) by PGPR provides numerous benefits, including enhancing plant resistance to phytopathogens and decreasing fungal, bacterial, and nematode diseases. Several microbial genera, including *Bacillus, Pseudomonas, Arthrobacter, Serratia, and Stenotrophomonas*, have specialized bacterial species that affect plant growth. *Bacillus* spp. produce effective VOCs, such as 2-butanediol and acetoin, to limit fungal spread and promote plant growth (Santoro et al., 2016).

3.2.4 Production of Exopolysaccharide (EPS)

Different species of algae, bacteria, and plants produce biodegradable polymers known as EPSs. Algae, bacteria, and plants make EPS from glucose residues and their analogs (Sanlibaba and Cakmak, 2016). EPSs help the host survive stress conditions such as salty soil, dryness, or excess moisture by storing water, aggregating soil particles, and enhancing the interaction of rhizobacteria with plant roots. EPS-producing PGPRs such as *Azotobacter, Rhizobium leguminosarum, Bacillus drentensis, Agrobacterium* sp., *Rhizobium* sp., and *Xanthomonas* sp., improve soil fertility and aid in farming. Mahmood et al. (2016) investigated how salt impacts mung bean growth, physiology, and yield. Researchers tested the effectiveness of foliar spraying with silicon (1 and 2 kg ha^{-1}) and two possible PGPRs (*B. drentensis and E. cloacae*) under harsh natural saline environments. PGPR and Si in agriculture can sustainably alleviate mung bean salinity stress.

3.2.5 Production of Antibiotic

Microbial antagonists can effectively attack plant diseases in crops, replacing traditional pesticides. PGPR, which produces antibiotics, plays a key role in controlling the spread of microorganisms that cause diseases such as *Bacillus* and *Pseudomonas*. Over the past 20 years, PGPR has produced medicines to fight against plant diseases and has been widely studied for biocontrol mechanisms (Ulloa-Ogaz et al., 2015). Antibiotics produce most of the *Pseudomonas*, including cepaciamide A, oomycin, viscosin, and A, ecomycins. *Pseudomonas* produces several drugs, including pyoluteorin, pyrrolnitrin, rhamnolipids, 2,4-diacetylphloroglucinol, and pyoluteorin. *Bacillus* species produce lipopeptide antibiotics including surfactin and bacillomycin, as well as other antifungal medicines and antibiotics. Bactericides are further classified as volatile or non-volatile. Non-volatile antibiotics include polyketides, aminopolyols, cyclic lipopeptides, and heterocyclic nitrogenous compounds. Volatile antibiotics can contain alcohols, aldehydes, ketones, and hydrogen cyanide (Fouzia et al., 2015).

3.2.6 Production of Plant Growth Hormone

Phytohormones and plant growth hormones affect growth and maturation of plant at low levels (<1 mM) (Damam et al., 2016). Bacteria that can influence the synthesis of growth regulator enzymes are known as phytostimulators. It may even urge plants to create phytohormones. The root cell produces high levels of auxins, abscisic acid, cytokinins, ethylene, gibberellins, and brassinosteroids. These substances have an impact on the roots' roots, hairs, and both sides, increasing the plant's ability to absorb water and nutrients. Endophytic and symbiotic bacteria near plant roots produce phytohormones that impact root system expansion for nutrient absorption, seed germination, vascular tissue development, flowering, shoot extension, and overall plant growth (Antar et al., 2021). PGPRs produce many compounds, including IAA, gibberellins, cytokinins, and ethylene synthesis inhibitors. PGPR-produced IAA phytostimulators impact plant growth, geotropism, phototropism, cell division, and root initiation (Nath et al., 2017). Tryptophan is a commonly found amino acid in root exudates. It is the major bacterial precursor molecule that produces IAA (Etesami et al., 2009). Microbes that produce IAA may be capable of removing hazardous quantities of tryptophan and their cells' analogs. Plant cytokinins promote lateral root development, cell division, and root hair growth while inhibiting root system expansion.

Gibberellins promote root lengthening, stem tissue, and elongation to the side. Ethanol, a key phytohormone, can impact plant growth and development through many biological mechanisms. It promotes seed germination, inhibits root elongation, facilitates fruit maturity, reduces leaf withering, increases crop yield, and stimulates plant hormone synthesis. Additionally, it plays an important role in root development. *Pantoea, Bacillus, Bacillus, Arthrobacter, Enterobacter, Pseudomonas, Burgholderia,* and *Brevundimonas,* are among the PGPRs known to produce phytostimulants (Kumar et al., 2014).

4. Utilizing PGPR in the Production of Vegetables

Several processes, including nutrient immobilization, nitrogen nitrification, organic matter mineralization, phosphate solubilization, and phytohormone synthesis, contribute to increased crop yield and soil fertility. Rhizobacteria linked to roots produce significant amounts of biomolecules in the soil, providing health advantages. PGPR produces a variety of volatile chemicals and molecules, including enzymes and proteins, which increase plant growth and soil quality. Bacteria from many genera, including *Bacillus, Arthrobacter, Pseudomonas,* and *Stenotrophomonas*, generate volatile chemicals (VanPeer and Schippers, 1989). As researchers learn more about the plant growth-promoting mechanism of PGPR, they anticipate increased tomato yield and fewer chemical inputs. Ethiopian researchers found that greenhouse conditions had varying impacts on tomato root development and the involvement of *Pseudomonas* leaves, stems, and isolates. The greatest fluctuating factor was the dry weight of the leaves (Fenta and Assefa, 2017). *B. subtilis* B2G and *Pseudomonas* APF1 treatments produced the greatest number of fresh and dry weight tomatoes reported (Lemessa and Zeller, 2007). *Trichoderma* and *Bacillus* spp. have set new standards for growth rates, fruit yield, and nutrient accessibility.

5. PGPR Used in Crops

Zea mays L., commonly referred to as maize, is a grain plant in the Poaceae family. It is one of the world's largest and most significant grain crops. The International Grains Council (Council, 2019) predicts that maize consumption will increase globally until 2024, particularly for animal feed. Maize, one of the world's three most significant crop species, accounts for over half of the daily energy needs of creatures in Africa and the Americas (FAOSTAT, 2020). Increasing maize output requires more fertilizer, which increases production costs and worsens environmental problems. Rhizobacteria have proven benefits for agricultural development and production by promoting plant growth. Kuan et al. (2016) propose PGPR as a biological solution for increasing crop yield, adjusting atmospheric nitrogen, and slowing maize nitrogen recovery. Plant-N remobilization is linked to plant aging, resulting in up to 39% increase in year rates with less input fertilizer-N. PGPR is beneficial for cereal crops, especially maize, as it increases grain output. Bacteria can create IAA and antibiotics, which improve plant nutrient absorption. Plant development is influenced by phosphorus solubilization and other PGPR features that have not yet been investigated. Researchers are also looking at the bioprotective properties of PGPR in maize crops. *Fusarium* is a harmful fungus commonly found in maize. Pereira et al. (2011) found that certain PGPR strains, such as *Microbacterium oleovorans*, *Bacillus amyloliquefaciens* and can prevent *Fusarium verticillioides* from infecting maize seeds.

Some PGPR species can function as both biofertilizers and biocontrol agents, potentially promoting plant growth. Isolates of *B. cepacia* have been found to have biocontrol potential against *Fusarium* spp. Bevivino et al. (1998) discovered that these bacteria can stimulate maize growth in low-iron settings by creating siderophores. Sugarcane is among the original and most important crops. This hybrid of the *Saccharum* plant has multiple applications in industry. Sugarcane thrives best in tropical and subtropical regions (Zhao and Li, 2015). Sugarcane generates biodiesel and biogas, making it a significant global resource. Compared to other approaches, PGPR offers environmental and economic benefits by increasing sugarcane output while reducing fertilizer use. Growing sugarcane on low-nutrient soil is a substantial difficulty, making it difficult to generate high yields. Phosphorus (P) has the highest impact on soil. Although less significant than K and N, it is crucial for sugarcane survival and root system development (Zuo and Zhang, 2011). Inadequate phosphorus availability is caused by a combination of variables such as lack of phosphorus in the original material, clay absorption, and precipitation with aluminum oxides, iron, and hydroxides. Sugarcane cultivation requires a significant amount of P fertilizers, which raises production prices. During the first year, much of the applied phosphorus fertilizer is fixed in the soil, making it unavailable to plants. But only 10–30% of this is absorbed by the roots of cane crops (Syers et al., 2008). Find phosphate-free fertilizers as soon as feasible. PGPR, an alternative to mineral fertilizers like P, can improve sugarcane performance while minimizing environmental effects (Spolaor et al., 2016). Several studies found that introducing three distinct PGPR species and five different doses into sugarcane of P increased crop yields and reduced fertilizer costs for farmers (Rosa et al., 2020). The study found that a mix of *Bacillus subtilis*, *Azospirillum umbrasilense,* and inexpensive (P_2O_5) fertilizer was the most beneficial for sugarcane output. Using *B. subtilis* and byproducts can enhance soil fertility, reduce the negative impacts of vinasse fertilization, promote root and shoot growth, and generate a synergistic effect, allowing for efficient sugarcane production with minimal environmental impact (Santos et al., 2018). Sugarcane cultivars treated with *Azospirillum* exhibited improved root systems, leading to increased water and nutrient absorption and perhaps higher yields (Moura et al., 2018). This study explored the interplay between water regime, cultivar, and *Azospirillum* inoculation on auxin pools in native plants.

6. Conclusions and Future Prospects

PGPR promotes sustainable agriculture by synthesizing phytohormones, fixing nitrogen, solubilizing phosphates, and controlling plant diseases naturally. Researchers have thoroughly examined the favorable effects of PGPR on numerous crops. Benefits include faster shoot and root growth, better nutrient absorption, and increased resistance to abiotic and biotic stressors. With limited resources and a changing climate, PGPR's capacity to improve plant development in severe conditions like salinity and drought is critical. In conclusion, PGPR shows promise as a plant growth enhancer for sustainable farming, perhaps leading to higher harvests with fewer chemical inputs. Additional field study and testing are needed to fully understand the possibility of PGPR and develop practical applications. These enhancements enable eco-friendly PGPR techniques that promote plant growth and crop production.

Acknowledgements

The authors are thankful to the Convenor, Prof. Sarita Srivastava, and Principal, Prof. Ajay Prakash Khare, CMP Degree College, University of Allahabad, for providing the necessary laboratory to carry out the research.

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