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Plant Growth Promoting Rhizobacteria as a sustainable solution for modern Agriculture

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Abstract

A large group of bacteria called "PGPR" inhabit the root zone of plants and contribute to their growth in small but important ways. The synthesis of siderophores, phytohormone production, phosphate solubilization, biological nitrogen fixation, and 1-amino-cyclopropane-1-carboxylate (ACC) deaminase are all examples of such systems. The role of PGPR in plant growth-promoting processes is currently the subject of intense study. A growing number of farmers are beginning to see PGPR as a viable alternative to chemical additives, fertilizers, and pesticides. Instead, they play an important mediating role in soil behavior, interacting both antagonistically and synergistically with other soil microbes. They also hold promise as agents of sustainable agriculture, which could lead to a return to biological methods rather than chemical ones for sustaining soil fertility and plant survival in trying conditions. In this article, we take a look back at what we know about the ways in which PGPR works in farming, as well as the traits and processes that encourage plant development.

Keywords: PGPR, Aminocyclopropane, Sustainable Agriculture, microbes, biological.

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Introduction

In order to support a significantly expanding global population, agricultural production needs to rise by 50% to provide for approximately 9 billion individuals by the year 2050 (Shah *et al*., 2021). However, the escalation of food production, along with the overuse of artificial fertilizers and degradation of cultivable land (Pastor *et al*., 2019), exacerbates the increase in greenhouse gas (GHG) emissions and their resulting effects on climate change. Change in climate has led to significant declines in the yields of essential cereal crops, with wheat experiencing a fall of around 5.5% and maize a decrease of 3.8% (Lipper *et al*., 2014). Climate change is increasingly evident, resulting in a substantial increase in worldwide temperatures and the prevalence of other abiotic stressors that negatively impact harvest output. Soil is the top layer of the earth, containing water, oxygen, minerals and various life forms. These components perform fundamental functions together. The rhizosphere is a specialized, densely populated soil zone rich in beneficial microorganisms, consisting of a thin layer of soil around the roots. In 1978, Kloepper and Schroth first found rhizospheric bacteria in plant growth-promoting rhizobacteria (PGPR). Rhizospheric bacteria inhabit the root surface (rhizoplane) or penetrate root tissues (Gray and Smith 2005). PGPR are classified as beneficial, harmful, or neutral based on their effects on plant growth and development. Plant growth is assisted by mechanisms including the direct synthesis of chemicals (phytohormones) that promote development and the enhancement of nutrient absorption from the soil or environment (Glick 1995). These effects of PGPR help plants by indirectly inducing the various mechanisms that reduce stress during infection, enhance the basal resistance of the plant or exert activity against pathogens (Glick 1995). Microbes are provided with a plentiful supply of energy and nutrients by the discharge of carbohydrates and amino acids into the rhizosphere by plants. The bacterial diversity in the vicinity of the roots is greater than that of the surrounding soil. The majority of rhizospheric organisms are situated within 50 µm of the root surface, and populations within just 10 µm can reach densities of up to 1.2 × 108 cells per cm^3 or 109–1 microbial cell per gram of soil. Bacterial cells typically occupy only 7–15% of the total root surface area, despite the high concentration of microorganisms in the rhizosphere (Foster *et al*. 1983; Pinton *et al*. 2001)

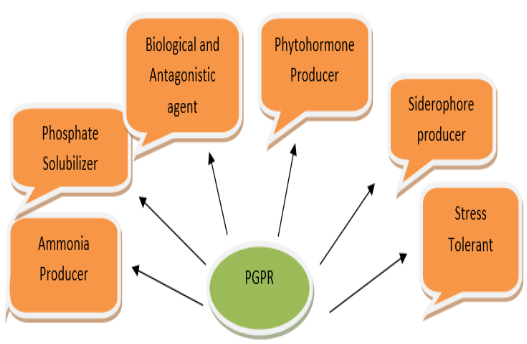

Figure 1: Showing different roles of PGPR in plant growth enhancement

PGPR: As an Ammonia Producer

One of the most important inorganic nitrogen sources for plants is ammonia. Ammonia triggers a cascade of morphological and physiological reactions in plants, including rapid alterations in gene expression, acidification of apoplasts, changes in cytosolic pH, and reorganization of the root system. Plant roots take up nitrogen in two forms: organic (urea, peptides, amino acids) and inorganic (ammonium, nitrates). Ammonium is taken up more readily than nitrates since it is a main nitrogen source (Miller *et al.* 2007). Agricultural crops only absorb around 35–65% of the nitrogen applied to them through nitrogen fertilizers. Excessive nitrogenous compounds are released into water, air, and soil during agricultural operations, posing a threat to both human and environmental health. Xu *et al.* (2012) note that there is a continuous attempt to mitigate this negative impact on agricultural productivity. PGPR is a viable alternative to nitrogen fertilizers since it gives plants readily available sources of nitrogen. In order to make ammonia, the Cappucina and Sherman 1992 process is used. The following methodology was followed to culture bacterial strains: 10 ml of peptone water was added to test containers, and the mixture was incubated at 30 ± 0.10°C for two days. Next, half a centiliter of Nessler's reagent was added to each tube; this caused a change in color from yellow to brown, signifying the presence of ammonia. Bacillus sp., Pseudomonas sp., and Acinetobacter sp. were identified in the rhizosphere of mung bean plants using this method, confirming the participation of PGPR in ammonia synthesis to improve plant growth (Punam Kumari *et al.* 2018).

PGPR: As a Phosphorus solubilizing agent

Phosphorus is a mineral that plants can't grow without. But plants can't take it up from the ground. Fertilizers that contain phosphorus have been used for a long time to help plants that are lacking in this element. The rocks that contain phosphate are the source of these fertilizers. Consequently, there has been a surge in the mining of phosphorous rocks. Phosphorus deficit affects over 5.7 billion hectares of land globally, which significantly reduces agricultural productivity (Mouazen and Kuang 2016). In order to supply plants with soluble and accessible forms of immobilized phosphorus, researchers are working hard to create revolutionary biotechnological approaches. The following PGPR aid in the conversion of immobilized phosphorus into plant-available forms by increasing its solubility. Plants inoculated with PGPR have shown to increase their uptake of phosphate, according to certain research. The phosphate concentration in the shoots of Lupinus albescens is nearly three times higher when inoculated with Sphingomonas sp., and of maize with Pseudomonas sp., according to Vyas and Gulati (2009) and Granada *et al*. (2013), respectively. Bacillus megaterium, Enterobacter, and Arthrobacter chlorophenolicus inoculation increases wheat grain yield by a factor of two and improve straw phosphate levels (Kumar *et al*. 2014).

PGPR: Antagonistic and biological agents

Bacteria that operate as biocontrol agents reduce the impact of plant diseases, whereas bacteria that act as antagonists fight off harmful pathogens. Caused by the synthesis of hydrolytic enzymes including glucanases, lipases, and chitinases, which destroy harmful cells, these effects are obtained (Neeraja *et al*. 2010; Maksimov *et al*. 2011). Through PGPR, antagonistic antibiotics and bacteriocins are produced. Microbes and their metabolism can be slowed or stopped by tiny, varied chemical molecules called antibiotics (Duffy 2003). As biocontrol agents against root infections, the six main classes of antibiotics include pyoluteorin, cyclic lipopeptides, pyrrolnitrin, hydrogen cyanide, and ploroglucinols (Haas and Degago 2005). Bacillus cereus strain UW85 targets oomycete infections and produces kanosamine and zwittermicin A, two biocontrol agents against alfalfa damping-off (Silo-Suh *et al*. 1994; He *et al*. 1994). In contrast to antibiotics, bacteriocins only kill bacteria that are very similar to the one that produced them (Riley and Wertz 2002). The wide suppression range of bacteriocins from Bacillus sp. makes them stand apart from other gram-negative bacteria, fungus, and yeast (Abriouel *et al*. 2011). One example of a protein found in gram-negative bacteria is colicin, which is produced by Escherichia coli. In order to protect plants from diseases, PGPR uses biocontrol agents to trigger a defense response called Induced Systemic Resistance (ISR) (Van Loon *et al*. 1998). Critical rhizobacteria for ISR activation include Pseudomonas and Bacillus sp.; ISR, like SAR, strengthens healthy plant tissues against infection (Van Wees *et al*. 1997; Van Loon *et al*. 1998) (Kloepper *et al*. 2004; Van Wees *et al*. 2008).

PGPR: As Phytohormone Producer

The word "phytohormone" was first used by Starling to describe organic molecules that are made in tiny amounts in one part of a plant and then moved to another part of the plant to control some physiological process. Auxins, cytokinins, gibberellins, abscisic acid, and ethylene are some of the most important plant hormones that aid in growth and development. Because of the positive interactions between plants and microbes, phytohormones—which are also produced by PGPR—have received a lot of attention. Plant cells and the PGPR work together to produce phytohormones, which are crucial for plant development and growth. For example, according to Siddiqui (2006), PGPR controls the rhizosphere microbial populations, which impact root growth, seed germination, and water efficiency. Bacterial inoculants are agricultural preparations that include helpful microbes. They help plants grow by stimulating the rhizosphere to produce more phytohormones. Extensive research has been conducted on the production of phytohormones and growth regulators in Azospirillum species, including auxins, ethylene, gibberellins, cytokinins, abscisic acid, and nitric oxide and polyamines (Cassan *et al*. 2014). Bacillus amyloliquefaciens produces salicylic acid, gibberellins, and auxins at high quantities in chemically specified media. In addition, Masciarelli *et al*. (2014) found that soybean nodule development is enhanced when Bradyrhizobium japonicum and Bacillus amyloliquefaciens are co-inoculated. Essential for plant vitality, development, and growth, Indole-3-acetic acid (IAA) plays a pivotal role in these processes. Microbacterium, Bacillus, Methylophages, Paenibacillus, and Agromyces are some of the bacterial species that produce indoleacetic acid (IAA), which greatly enhances root elongation in rice plants (Bal *et al*. 2013). Accelerated flowering, stem elongation, delayed aging, and seed dormancy can all be attributed to gibberellic acid (GA). Atzorn *et al*. (1988) first identified Rhizobium meliloti as the GA-producing bacterium. This led to the discovery that GA may be produced by Acetobacter diazotrophicus and Herbaspirillum seropedicae (Bastian *et al*. 1998). It has been shown that inoculating Pinus pinea with Bacillus licheniformis and Bacillus pumilus improves its growth (Probanza *et al*. 2002). Furthermore, Pseudomonas putida controls stress physiology in salty conditions and aids in soybean development (Kang *et al*. 2014). Cytokinins have an essential role in several biological processes, including cell division, seed germination, and the delay of senescence (Monk 1994). Klebsiella, Escherichia, Proteus, Bacillus, Agrobacterium, Xanthomonas, and Pseudomonas are among the bacterial genera that produce cytokinins (Akiyoshi *et al*. 1987; Garcia de Salamone *et al*. 2001; Karadeniz *et al*. 2006). You can't have root gravitropism, fruit ripening, or seedling growth inhibition without ethylene. Pseudomonas solanacearum infection causes bananas to ripen early, even though only a small number of bacterial genera produce ethylene (Freebrain and Buddenhagen 1964). Both Boiero *et al*. (2007) and Cohen *et al*. (2008) found that Azospirillum brasilense and Bradyrhizobium japonicum produce abscisic acid (ABA), which aids in seed dormancy and leaf abscission. Research conducted by Mahaheshwari *et al*. (2015) found that out of all these hormones, auxin or IAA had the most beneficial effects on crop productivity and biocontrol. Table 1 lists a few microorganisms that produce phytohormones.

Table 1: List of Phytohormones and their producing Bacteria.

Phytohormones	Bacteria	References
Auxin	*Methylophages,Bacillus, Agromyces, Microbacterium, Paenibacillus, Kocuriaturfanensis*	Bal *et al*. 2013 Goswami *et al*. 2014
Gibberellic Acid	*Sphingomonas, Bacillus*	Khan *et al*. 2014
Cytokinin	*Pseudomonas and Agrobacterium*	Akiyoshi *et al*. 1987
Ethylene	*Pseudomonas solanacearum, Pseudomonas syringae*	Freebairn and Buddenhagen 1964
Abscisic Acid	*Bradyrhizobium japonicum and Azospirillumbrasilense*	Boiero *et al*. 2007 Cohen *et al*. 2008

PGPR: Siderophore Production

Iron is the fourth most vital and prevalent element for the growth, metabolism and survival of most cells on Earth. It is extensively present in soil but infrequently detected in its free form. In an aerobic atmosphere, soluble iron undergoes oxidation, transforming into oxyhydroxides and insoluble ferric oxides, rendering the free form of iron immobile (Page 1993). Iron is essential for plants, microorganisms, and animals (Dudeja *et al*. 1997). It is a cellular component utilized as an electron transporter. Its deficit can induce a decline in DNA and RNA synthesis, growth inhibition, inhibition of sporulation, and alterations in cellular shape. It governs the manufacture of poisons, antibiotics, vitamins, siderophores, pigments, and other compounds. The ideal concentration of iron in the soil ranges from 24 to 42 ppm. A link exists between the iron content in soil and that in plants. Deficiency of iron in plants can be addressed through the application of iron chelates, the incorporation of organic matter into the soil, and the adjustment of soil pH; however, these methods are costly and inefficient for extensive use (Singh *et al.* 2024). Therefore, the utilization of microbes that produce siderophores is employed to enhance iron availability for plants (Chincholkar *et al*. 2000). There is ample evidence about iron absorption by plants via microbial siderophores. Iron-regulated membrane proteins are present on the cell surfaces of bacterial strains that produce siderophores. These proteins facilitate the transportation of ferric iron complexes across the membrane, thereby releasing iron for cellular metabolism (Johri *et al*. 2003). Siderophores are iron-binding compounds with a low molecular weight that are produced by microorganisms to address iron deficiency (Kintu *et al*. 2001). Nevertheless, siderophores may be deleterious at elevated concentrations (Guerinot 1994). They are produced by the majority of facultative anaerobic and aerobic microorganisms, with the exception of Lactobacilli (Loper and Buyer 1991). (Konetschny *et al*. 1990) have classified siderophores into two primary categories based on their primary chelating groups: (i) Hydroxamates and (ii) Carboxylates (Catecholates). In a modified succinic acid medium, Pseudomonas fluorescens NCIM5096 and Pseudomonas putida NCIM2847 generate hydroxamate-type siderophores (Sayyed *et al*. 2005). In pot culture conditions, the inoculation of Pseudomonas fluorescens NCIM5096 improves the germination of seeds and the length of shoots and roots in wheat. According to Sayyed *et al*. (2007), the germination and growth of Withania somnifera and Chlorophytum borivillianum have been observed in both plate assays and pot assays under natural soil conditions. The siderophore-rich broth from Arthrobacter feacalis was produced under iron-deficient conditions in a succinic acid medium. Sayyed *et al*. (2007) also reported an increase in the germination rate of C. borivillianum tubers. Therefore, the biological application or inoculation of siderophore-producing microbes is a sustainable approach to improving crop productivity, increasing organic matter, and enhancing soil enzymes, in addition to the potential benefits of disease suppression and plant growth promotion (Sayyed *et al*. 2004). Some siderophore-producing bacteria are listed below in table 2.

Table 2 List of Siderophore and their producing bacteria (Sayyed *et al*. 2013).

Siderophore	Bacteria
Azotochelin	*Azotobacter vinelandii*
Agrobactin	*Agrobacterium tumefaciens*
Cepabactin	*Pseudomonas cepacian*
Enterobactin	*E.coli*
Pyochelin	*Pseudomonas aeruginosa*
Pyoverdin	*Pseudomonas sp.* *P. fluorescens* *P. putida*
Arthrobactin	*Arthrobacter sp.*
Francobactin	*Frankia sp.*
Schizokinen	*Bacillus megaterium*
Yersiniophore	*Yersinia enterocolitica*

PGPR: As Stress tolerant

The global population is rapidly increasing, posing a challenge for agricultural food production to sustain this expanding demographic. The advancing community is directly influenced by numerous causes, including environmental degradation, constraints on arable land, and other abiotic and biotic pressures that impact global food production. Multiple strategies are required to meet food demand, including increased utilization of pesticides, chemical fertilizers, and herbicides, as well as addressing salinity, heat, and drought-related land pressures. Nonetheless, these methods are unsustainable and detrimental to the environment. Approximately 7.6 million km² of territory is globally impacted by such adverse environmental variables (Christensen *et al*. 2007).

Before evaluating the potential of rhizobacteria to promote plant growth, it is imperative to comprehend the mechanisms of microbial recruitment in the rhizosphere and the effects of root exudation (Drogue *et al*. 2012; Patel *et al*. 2017). Research has shown that Pseudomonas monteilli, Cronobacter dublinensis, and Bacillus sp. can improve nutrient assimilation and reduce abiotic stress in Ocimum basilicum L. (Rakshapal *et al*. 2013). Ion flux in plants is predominantly disrupted by salinity. Certain rhizobacteria, including Azospirillum sp. and Pseudomonas sp., have been demonstrated to enhance biomass and growth by modulating the availability of essential nutrients and oxidative stress enzymes in saline conditions (Noorieh *et al*. 2013). Mechanisms such as hydraulic conductance, enhanced photosynthetic processes, and osmotic accumulation, among others, may contribute to the salinity tolerance of PGPR (Dodd and Perez-Alfocea 2012). Pseudomonas sp. and Serratia sp. show beneficial characteristics, including phosphate solubilization, nitrogen fixation, and IAA production, particularly in the presence of salinity stress. Pseudomonas sp. is currently being evaluated for its potential to improve seed germination in Oryza sativa (Nakbanpote *et al*. (2014). Achromobacter piechaudii, which possesses ACC deaminase activity, enhanced the biomass of pepper and tomato plants in drought conditions, thereby enabling the plants to withstand water deficiency. Plants that are colonized by PGPR have been demonstrated to produce less ethylene, which mitigates the effects of water scarcity without substantially altering their relative water content (Myak *et al*. 2004). Inoculating maize plants with Mycobacterium phlei MbP18, Bacillus polymyxa BcP26, and Pseudomonas alcaligenes PsA15 under heavy metal stress led to improved nutrient uptake and growth. In contrast to fruitful loamy sand soils, roots that were growing in nutrient-deficient calcareous soils exhibited an increased assimilation of nitrogen, phosphorus, and potassium (Egamberdiyeva 2007). Research suggests that PGPR also improves plant tolerance to chilling injuries (Ait Barka *et al*. 2006) and high-temperature stresses (Ali *et al*. 2009). Furthermore, Pseudomonas putida has been recognized as a beneficial agent for temperature tolerance (Ali *et al*. 2011). Consequently, PGPR can assist in the maintenance of the fertility of sustainable agricultural lands, the reduction of the dependence on chemical inputs, and the balance of soil nutrients.

Conclusion

An effective sustainable agriculture system enhances and preserves human health, safeguards the environment, generates sufficient food for a growing global population, and provides spiritual and economic advantages to both producers and consumers. Biotic and abiotic pressures present in the environment are significant limits to global agricultural productivity. PGPR present a compelling solution to this issue as they provide resistance to various stresses and possess multifunctional capabilities to augment crop yield, mitigate environmental pollution, facilitate the development of novel inoculants, and promote eco-friendly sustainable agricultural growth via methods such as nitrogen fixation, phosphate solubilization, ammonia production, siderophore synthesis, and hormone production, among others. The diversity, method of action, host specificity, colonization ability, applications, and formulations of PGPR are directly pertinent to their utilization in horticulture, agriculture, and agroforestry for sustainable plant development and growth. Despite considerable progress in comprehending the factors that facilitate PGPR root colonization, metabolic status, mechanisms of action, dispersal, and interactions with host plants, results remain inconsistent due to challenges such as screening programs, application, and formulation. Consequently, PGPR has not yet realized its potential and promise as commercial inoculants. Ongoing efforts are necessary to improve plant growth, increase competitiveness, and enhance capabilities through genetic engineering or selection in an economically viable and efficient manner in the development of PGPR formulations. This should aim for sustainable success across diverse soil conditions, host cultivars, and climates by acquiring knowledge of the genes and characters required in the interaction between PGPR and roots. In addition to understanding PGPR, its application, and efficiency, there must be heightened awareness regarding its use and adoption, a robust relationship between researchers and entrepreneurs, and the necessity for new strategies to minimize chemical treatments for sustainable agriculture, thereby leveraging all beneficial factors and mechanisms of action of PGPR in agricultural practices.

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