Biological Forum – An International Journal **17(1): 90-94(2025)**

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

Plant Growth Promoting Rhizobacteria: Mechanisms and their Role in Sustainable Agriculture

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(Received: 15 October 2024; Revised: 29 November 2024; Accepted: 20 December 2024; Published online: 18 January 2025)
(Published by Research Trend)

ABSTRACT: The soil rhizosphere is teeming with diverse microorganisms, including fungi, bacteria, protozoa, and algae. Among them, bacteria are the most abundant and can be either plant pathogenic or beneficial. Plant Growth Promoting Rhizobacteria (PGPR) are the microbes that occur naturally, free-living in nature that exist in the soil and are important for promoting plant growth. PGPR are beneficial microorganisms that reside in rhizosphere and significantly contribute to plant growth and productivity. These bacteria employ a diverse array of mechanisms to promote plant growth, which can be broadly categorized into direct and indirect mechanisms. Direct mechanisms include nitrogen fixation, phytohormone production and phosphate solubilization which collectively improve plant nutrient uptake and physiological functions. Indirect mechanisms involve the suppression of phytopathogens through the production of antimicrobial compounds, competition for resources and induction of systemic resistance in plants. This review explores the multifaceted mechanisms employed by PGPR, emphasizing their role in sustainable agriculture.

Keywords: Rhizosphere, Plant Growth Promoting Rhizobacteria (PGPR), direct nitrogen fixation, phosphate solubilization, HCN production, Competition.

INTRODUCTION

Variety of biotic and abiotic factors influence the plant growth. The rhizosphere, a thin layer of soil immediately around the roots, is vital for root activity. The term "rhizosphere" was first used by Hiltner, who defined it as the little area of soil that surrounds roots and is where root activity stimulates the growth of microorganisms.

The soil rhizosphere is inhabited by a variety of microorganisms, including bacteria, fungi, protozoa, and algae, with bacteria being the most prevalent (Sivasakti *et al.*, 2014). Soil rhizosphere is also known as storehouse of microbes as it contains different microorganisms and important for microbial activity (Kundan *et al.*, 2015). In addition to providing habitat and resource variability for soil organisms, the rhizosphere is the location of organic deposition (Bajeli *et al.*, 2023).

Sustainable agriculture, or organic farming, avoids many of the social and environmental problems that plague conventional farming (Wani and Kumar 2024).

Plant-associated bacteria can be either plant growth-promoting rhizobacteria (PGPR) or plant pathogenic bacteria. Plant growth promoting rhizobacteria (PGPR) are bacteria that live in roots and promote plant growth. By assembling growth-promoting compounds, they increase the host plant's availability of micronutrients, which has a major effect on growth and development. They are also widely known for their contribution to better root growth patterns. Exudates from the roots contain a vast array of organic molecules that serve as a signal to draw in soil bacteria, which are a rich source of carbon in the soil (Drogue *et al.*, 2013).

Free-living soil-borne rhizobacteria that promote plant growth have the ability to accelerate plant growth. *Azotobacter, Azospirillum, Pseudomonas, Acetobacter, Burkholderia, Bacillus, Paenibacillus,* and a few members of the Enterobacteriaceae family are among the genera that are included in PGPR. They can reduce soil-borne diseases at the rhizosphere, quickly colonize the rhizosphere, and promote plant growth, can have direct effect on a plant's metabolism by controlling the breakdown or production of different phytohormones (Bloemberg and Lugtenberg 2001; Rangarajan *et al.*, 2003; Bajeli *et al.*, 2023). Plant growth-promoting rhizobacteria (PGPR) offer a promising strategy for enhancing sustainable agriculture despite environmental stress (Parnate *et al.*, 2024).

A variety of secondary metabolites, including siderophores, phytohormones, antibiotics, and volatile chemicals, can be produced by PGPRs. Of these, the creation of indole-3-acetic acid, siderophores, and antibiotics are the primary substances that contribute to the bacteria's ability to promote plant growth. Also, PGPRs have the ability to decompose organic matter present in soil which have crucial role in plant production (Mohamed *et al.*, 2019).

Commercialized as pesticide substitutes, microbial bio-inoculants, and bio-fertilizers, PGPRs that were isolated and screened from rhizospheric soils have been utilized as agricultural inputs to boost plant development and yields by reducing plant illnesses (biological control) (Nazneen *et al.*, 2022). Different mechanisms exerted by PGPR helps in enhancing the plant production and combating different plant diseases which eventually helps in increased yield and sustainable agriculture.

— Major role of these PGPR includes (Kundan *et al.*, 2015):

(a) Provision of nutrients to the plants

(b) Increasing plant growth by generating various phytohormones

(c) Control or inhibition of activity of phytopathogens

(d) Bio-accumulation or microbial leaching of inorganic compounds

PGPR are classified into two groups according to their relationship with plants:

(a) Free-living rhizobacteria

(b) Symbiotic bacteria

PGPR exerts direct or indirect mechanism which influence the plant growth.

— Mechanism of PGPR

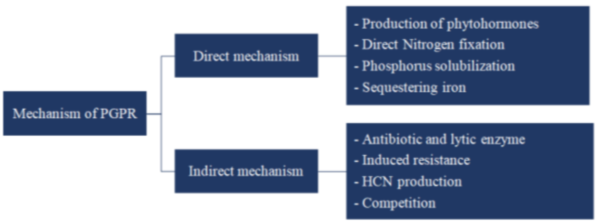

Fig. 1. Direct and Indirect mechanisms of PGPRs.

Direct mechanism

(a) Production of phytohormones:

— Production of indole acetic acid (IAA): The most extensively researched auxin, IAA, is responsible for cell division, elongation, differentiation, and extension. According to Saharan and Nehra (2011), bacteria employ IAA to interact with plants during colonization, including phytostimulation and evading the plant's defence mechanisms. Sweet potato cultivar inoculated with IAA producing isolates significantly improves plant growth by absorbing N, P, K, Ca and Mg (Farzana and Radizah 2005). Studies reported role of IAA production in *Lysinibacillus* spp. strains which showed that proliferation of lateral roots was significantly impacted by PGP activity. Also, all strains produced IAA between 20-70 µg/mL range (Pantoj-Guerra *et al.*, 2023). In the presence of 10000µg/ml L-tryptophan *Bacillus aerius* produces 7µg/ml auxin while in the case of pot experiment inoculation with strains Z-54 and Z-16 produced maximum value of shoot length and fresh weight of *Vigna radiata* (Saboor *et al.*, 2024). 24 PGPR strains isolated from the roots and rhizosphere of *Ceanothus velutinus*, a native plant in the intermountain west region of the USA. Of them, 17 isolates generated IAA levels greater than 10 µg/mL. In *Arabidopsis thaliana*, strains CK-6, CK-22, CK-41, CK-44, CK-47, CK-50, CK-53, and CK-55 notably enhanced shoot biomass. One of these isolates (CK-55) was recognized as *Sphingobium*, whereas the others were classified as *Pseudomonas* (Ganesh *et al.*, 2024).

— Production of cytokinins and gibberellins: Cytokinins is responsible for cell growth and differentiation as well as apical dominance is also promoted by them. PGPR can produce them in soil and also in pure culture. Gibberellins are produced naturally by plants which influence developmental process of plants like germination, flowering, stem elongation, fruit senescence (Kundan *et al.*, 2015). Certain PGPR strains are known to produce cytokinins, thereby stimulating plant growth. For instance, *Azospirillum brasilense* has been reported to produce cytokinins, contributing to enhanced plant growth and activation of antioxidant and physiological systems (Zaheer *et al.*, 2022). Research has indicated that certain PGPR strains, including *Bacillus subtilis* and *Bacillus toyonensis*, produce cytokinins contributing to plant growth promotion (Biswas *et al.*, 2024).

(b) Direct nitrogen fixation: Nitrogen fixation is the process of converting atmospheric nitrogen into usable nitrogen that transforms into ammonia. At moderate temperatures, nitrogen-fixing bacteria carry out biological nitrogen fixation. The rhizosphere of plants is known to be colonized by a variety of bacterial species belonging to the genera *Azospirillum*, *Alcaligenes*, *Arthrobacter*, *Acinetobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Pseudomonas*, *Rhizobium*, and *Serratia*. By having a variety of advantageous impacts, these bacteria greatly aid in the growth of plants by directly fixing the nitrogen (Kundan *et al.*, 2015).

Table 1: Nitrogen fixing bacteria and their relationship with the host plants (Kundan *et al.*, 2015).

PGPR	Relationship	Host plant
Azospirillium sp.	Non-symbiotic	Rice, wheat, maize, sugarcane
Azotobacter sp.	Non-symbiotic (aerobic)	Paspalumnotatum grass, maize, wheat
Azoarcus sp.	Non-symbiotic(aerobic/microaerophilic)	Kallar grass, sorghum
Acetobacter sp.	Non-symbiotic (obligatory aerobic)	Sugarcane
Rhizobium leguminosarum	Symbiotic (endosymbiotic)	Wheat, maize, barley
Bradyrhizobium betae	Symbiotic	Sugar beets
Bradyrhizobium japonicum	Symbiotic	Cowpeas, mungbeans, soybeans
Burkholderia sp.	Symbiotic (endo)	Rice

Pseudomonas spp., a genus of PGPR, differ from other PGPR genera in several ways, including nitrogen fixation and root colonization. These bacteria not only fix atmospheric nitrogen but also produce bioactive metabolites and siderophores that combat plant pathogens, further supporting plant health and growth (Singh *et al.*, 2024).

(c) Phosphate solubilization: Phosphate solubilizing bacteria converts the inorganic form of phosphorus into the available form which is required for plant growth. *Bacillus, Rhizobium, and Pseudomonas* are the most effective genera of bacteria that solubilize phosphate. In general, bacteria solubilize phosphate in two ways: (1) by releasing organic acid and altering phosphorus mobility through ionic interactions, and (2) by using phosphatases, which aid in the unbinding of phosphate groups from organic matter (Kundan *et al.*, 2015). *Pantoea* isolates HCF6 and HCF9 isolated from the closed flowers of *Hedychium coronarium* demonstrated efficient solubilization of calcium phosphate ($Ca_3(PO_4)_2$) and aluminum phosphate ($AlPO_4$). Inoculation of wheat plants with these isolates under phosphorus-deficient conditions resulted in increased root and shoot lengths, enhanced plant dry mass, and higher phosphorus content in plant tissues (Prasad *et al.*, 2022).

Table 2: Phosphate solubilizing bacteria with their host plants (Kundan *et al.*, 2015).

PGPR	Host plant
Azotobacter chroococcum	Wheat
Bacillus circulans, Cladosporium herbarum	Mungbeans
Bradyrhizobium japonicum	Soybeans
Enterobacter agglomerans	Tomato
Pseudomonas chlororaphis, Pseudomonas putida	Soybeans
Rhizobium leguminosarum	Beans (*Phaseolus vulgaris*)
Bacillus megaterium	Tea

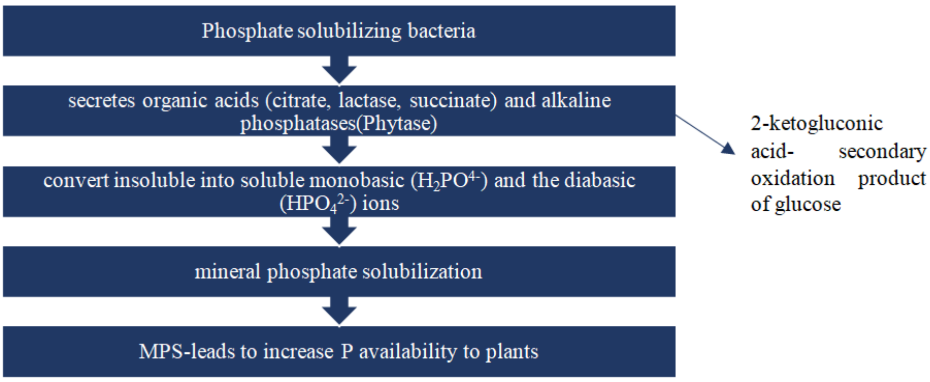

Fig. 2. Flow chart showing phosphorus solubilization by the PGPRs (Yadav *et al.*, 2022).

Indirect mechanism: Indirect mechanism involves the ability of PGPR to reduce the harmful effects of plant pathogens on the growth (Kundan *et al*., 2015).

(d) HCN production: Rhizobacteria are biocontrol agents that have the ability to colonize plant root surfaces and inhibit plant growth. Many microorganisms, including bacteria, algae, fungus, and plants, produce the poisonous chemical cyanide as a strategy of surviving by outcompeting their counterparts. Inoculation with cyanide-producing bacterial strains usually has no adverse effects on the host plants. The majority of HCN is produced by *Bacillus* and *Pseudomonas* species. Cell death is thought to result from HCN's inhibition of the electron transport chain and the cell's energy source. Additionally, it appears that PGPR inhibits the reversible process of inhibition of natural receptors and enzymes, and it is also known to limit the action of cytochrome oxidase. PGPR strains isolated from the sorghum rhizosphere and used to assess their plant growth-promoting traits which showed HCN production under controlled condition. The study found that certain isolates, such as *Bacillus subtilis* (PG-152), exhibited multiple beneficial traits, including HCN production, which contributed to enhanced plant growth and biocontrol of pathogens (Chiranjeevi *et al.*, 2024).

(e) Competition: Sometimes, PGPR competes for nutrients with hazardous microorganisms that are present in trace amounts, which can limit the disease-causing agent. This is evident when the soil contains a large number of non-pathogenic microorganisms that quickly colonize plant surfaces, consume up available nutrients, and so prevent the growth of pathogenic germs. When the pepper plant infected with the *Alternaria alternata* was inoculated with *Bacillus amyloliquefaciens* RaSh1 PGPR strain it showed 40 percent disease incidence while plants with infection of *A. alternata* alone recorded 80 percent disease incidence (Soliman *et al.*, 2023).

These mechanisms are critical yet challenging to study within the system. Among them, nutrient competition between PGPR and pathogens stands out as the most significant interaction. This competition indirectly promotes plant growth by suppressing pathogen development.

Table 3: PGPR having the ability to biocontrol several diseases in the host plant (Kundan *et al.*, 2015).

PGPR	Host plant	Pathogen
Bacillus pumilus	Tobacco	Blue mold
Bacillus subtilis and *B. cereus*	Wheat	*Rhizoctonia solani* AG 8
B. subtilis CE1	Maize	*Fusarium verticilloides*
Pseudomonas sp.	Groundnut	*Rhizoctonia bataticola*
Pseudomonas chlororaphis	Sorghum	*Macrophominaphaseolina*
Pseudomonas fluorescens	Wheat and barley	*Fusarium culmorum*
Enterobacter sp.	Chickpea	*Fusarium avenaceum*

(f) Induced systemic resistance (ISR): When a plant pathogen attacks, ISR is triggered. It is a process that results in enhanced resistance at certain plant locations after induction. It aids in the plant's disease control but is not pathogen-specific. It involves the plants receiving signals from jasmonate and ethylene, which are hormones that boost the host plant's defence mechanisms against a variety of diseases (Kundan *et al.*, 2015). Systemic resistance in tomato was induced by PGPR strain *Bacillus cereus* AR156 by modulating the WRKY8 transcription factor. This modulation enhances the plant's defence against pathogens and contributes to improved development under stressful circumstances (Li *et al.*, 2023).

CONCLUSIONS

Plant growth-promoting rhizobacteria (PGPR) contribute significantly to increasing plant production and growth through a variety of direct and indirect ways. By facilitating synthesization of growth-promoting phytohormones and inducing systemic resistance, PGPR contribute significantly to plant health and resilience. Advancements in molecular and genomic technologies have deepened our understanding of PGPR functionality, enabling the development of targeted bioinoculants and tailored agricultural practices. However, harnessing their full potential requires further research into strain-specific effects, plant-microbe interactions, and field-level performance under diverse environmental conditions. We can create resilient, resource-efficient, and environmentally friendly crop production methods that satisfy the needs of a growing world population by incorporating PGPR into agricultural systems.

FUTURE SCOPE

The future scope of Plant Growth Promoting Rhizobacteria (PGPR) in sustainable agriculture is vast, driven by the need for eco-friendly solutions to enhance crop productivity and soil health. Advances in biotechnology and precision agriculture are paving the way for customized PGPR formulations tailored to specific crops and environmental conditions. The integration of PGPR with organic and regenerative farming practices can significantly reduce dependency on chemical fertilizers and pesticides, promoting long-term soil fertility and biodiversity. Furthermore, research on stress-tolerant PGPR strains can help mitigate the effects of climate change, including drought, salinity, and heavy metal contamination. The application of omics technologies, such as metagenomics and transcriptomics, is expected to unveil new PGPR strains with enhanced growth-promoting capabilities. Additionally, innovations in microbial delivery systems, including nano-formulations and seed coatings, can improve the efficacy and stability of PGPR in agricultural systems. With increasing global awareness and policy support for sustainable farming, the commercialization of PGPR-based biofertilizers and biopesticides is expected to expand, offering cost-effective and environmentally friendly alternatives for farmers worldwide.

REFERENCES

Bajeli, J., Rai, P.N., Srivastava, R., Singh, A. V., Verma, A. and Negi, A. (2023). Seed germination enhancement through plant growth promoting rhizobacteria (PGPR) isolated from papaya rhizosphere. *Biological Forum – An International Journal, 15*(8), 36-41.

Biswas, D., Chakraborty, A. K., Srivastava, V. and Mandal, A. (2024). Plant Growth Promoting Rhizobacteria (PGPR): Reports on their colonization, beneficial activities, and use as bioinoculant. *Advances in agriculture, 1*, 1-15.

Bloemberg, G. V. and Lugtenberg, B. J. J. (2001). Molecular basis of plant growth promotion and biocontrol by rhizobacteria. *Current Opinion in Plant Biology, 4*(4), 343-350.

Chiranjeevi, M., Goudar, G. D., PU, K. and Yalavarthi, N. (2024). Study on effect of plant growth promoting rhizobacteria on sorghum (*Sorghum bicolor* L.) under gnotobiotic conditions. *Frontiers in Microbiology, 15*, 1-15.

Drogue, B., Combes-Meynet, E., Moenne-Loccoz, Y., Wisniewski-Dye, F., and Prigent-Combaret, C. (2013). Control of the cooperation between plant growth-promoting rhizobacteria and crops by rhizosphere signals. *Molecular Microbiology and Ecology of Rhizosphere, 1 & 2*, 279-293.

Farzana, Y. and Radizah, O. (2005). Influence of rhizobacterial inoculation on growth of the sweet potato cultivar. *American Journal of Biochemistry and Biotechnology, 1*(3), 176-179.

Ganesh, J., Hewitt, K., Devkota, A. R., Wilson, T. and Kaundal, A. (2024). IAA-producing plant growth promoting rhizobacteria from *Ceanothus velutinus* enhance cutting propagation efficiency and Arabidopsis biomass. *Frontiers in Plant Science, 15*, 1-13.

Kundan, R., Pant, G., Jadon, N. and Agrawal, P. K. (2015). Plant growth promoting rhizobacteria: mechanism and current prospective. *Journal of Fertilizers and Pesticides, 6*(2), 1-9.

Li, Z. J., Tang, S. Y., Gao, H. S., Ren, J. Y., Xu, P. L., Dong, W. P., Zheng, Y., Yang, W., Yu, Y. Y., Luo, J. H., Niu. D. D. and Jiang, C. H. (2024). Plant growth-promoting rhizobacterium *Bacillus cereus* AR156 induced systemic resistance against multiple pathogens by priming of camalexin synthesis. *Plant, Cell and Environment*, *47*(1), 337-353.

Mohamed, I., Eid, K. E., Abbas, M. H., Salem, A. A., Ahmed, N., Ali, M. and Fang, C. (2019). Use of plant growth promoting Rhizobacteria (PGPR) and mycorrhizae to improve the growth and nutrient utilization of common bean in a soil infected with white rot fungi. *Ecotoxicology and Environmental Safety*, *171*, 539-548.

Nazneen, H., Venu, E., Sen, K., Kumar, R., Ray, K., Barman, A. R., Ray, S. K., Mandal, R. and Dutta, S. (2022). Efficient native plant growth promoting rhizobacteria and their role in plant growth promotion and management of damping off disease in cowpea. *Biological Forum–An International Journal*, *14*(4a), 148-154.

Pantoj-Guerra, M., Burkett-Cadena, M., Cadena, J., Dunlap, C. A. and Ramirez, C. A. (2023). *Lysinibacillus* spp.: an IAA-producing endospore forming-bacteria that promotes plant growth. *Antonie van Leeuwenhoek*, *116*, 615–630.

Parnate, T. N., Bharose, A. A., Dudhare, M. S. and Dhawale, R. N. (2024). Studies on Effect of PGPR on Wheat (*Triticum aestivum* L.) for Mitigation of Water Stress. *Biological Forum – An International Journal*, *16*(10), 109-116.

Prasad, P., Kalam, S., Sharma, N. K., Podile, A. R. and Das, S. N. (2022). Phosphate solubilization and plant growth promotion by two *Pantoea* strains isolated from the flowers of *Hedychium coronarium* L. *Frontiers in Agronomy*, *4*, 1-10.

Rangarajan, S., Loganathan, P., Saleena, L. M. and Nair, S. (2003). Diversity of *Pseudomonas* isolated from three different plant rhizospheres. *Journal of Applied Microbiology, 91*(4), 742–749.

Saboor, M., Navid, S. and Ali, B. (2024). Screening *Bacillus* strains for auxin production and their potential to stimulate the growth of *Vigna radiata* (L.). *Pak-Euro Journal of Medical and Life Sciences*, *7*(3), 511-520.

Saharan, B. S. and Nehra, V. (2011). Plant growth promoting rhizobacteria: acritical review. *Life Sciences and Medicine Research*, *21*(1), 1-30.

Singh, P., Singh, R. K., Li, H. B., Guo, D. J., Sharma, A. Verma, K. K., Solanki, M. K., Upadhyay, S. K., Lakshmanan, P., Yang, L. T. and Li, Y. R. (2024). Nitrogen fixation and phytohormone stimulation of sugarcane plant through plant growth promoting diazotrophic *Pseudomonas*. *Biotechnology and Genetic Engineering Reviews*, *40*(1), 15-35.

Sivasakti, S., Usharani, G. and Saranraj, P. (2014). Biocontrol potentiality of plant growth promoting bacteria (PGPR) - *Pseudomonas fluorescens* and *Bacillus subtilis*: A review. *African Journal of Agricultural Research*,*9*(16), 1265-1277.

Soliman, S. A., Abdelhameed, R. E. and Metwally, R. A. (2023). *In vivo* and *In vitro* evaluation of the antifungal activity of the PGPR *Bacillus amyloliquefaciens* RaSh1 (MZ945930) against *Alternaria alternata* with growth promotion influences on *Capsicum annuum* L. plants. *Microbial Cell Factories*, *22*(70), 1-20.

Wani, Khursheed and Kumar, Deepak (2024). Sustainability in Organic Agriculture: Evaluating Environmental and Socioeconomic Benefits. *AgriBio Innovations*, *1*(1), 09-19.

Yadav, J., Mahawer, A. K., Prashantha, S. T. and Sagar, H. P. (2022). Plant growth-promoting rhizobacteria (PGPRS) and their mechanisms of action. *Biotica Research Today*, *4*(2), 103-105.

Zaheer, M. S., Ali, H. H., Iqbal, M. A., Erinle, K. O., Javed, T., Iqbal, J., Hashmi, M. I. U., Mumtaz, M. Z., Salama, E. A. A., Kalaji, H. M., Wrobel, J. and Dessoky, E. S. (2022). Cytokinin production by *Azospirillum brasilense* contributes to increase in growth, yield, antioxidant, and physiological systems of wheat (*Triticum aestivum* L.). *Frontiers in Microbiology*, *13*, 1-11.

How to cite this article: S.A. Rathod, D.S. Rabari and S.S. Kansara (2025). Plant Growth Promoting Rhizobacteria: Mechanisms and Their Role in Sustainable Agriculture. *Biological Forum – An International Journal, 17*(1): 90-94.