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Review

Significant Role of Plant Growth Promoting Rhizobacteria in Agriculture Field

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Abstract: Rapid population growth in the modern era has been associated with serious problems in the worldwide agro-ecosystems, which have resulted in lower production and a degradation of sustainable agro-ecosystems. Phytomicrobiome is one of the most effective methods, a superior option for agricultural sustainability and resolving both the issues of sustainability in the environment and worldwide food security. Plant growth-promoting rhizobacteria (PGPR) are free-living soil bacteria that may have both direct and indirect impacts on the growth of plants. The metabolism of plants can be significantly affected by bacteria that support the growth of plants and utilize their own metabolic pathway to dissolve phosphates, fix nitrogen, and develop hormones. Plant-beneficial rhizobacteria may reduce the world's dependency on dangerous chemicals for agriculture that disrupt agroecosystems. PGPR provides farmers with a great alternative to lowering their use of artificial pesticides and fertilizers without having a negative impact on the environment or reducing crop yields. The use of PGPR as formulations or bioinoculants is a very efficient technique to increase agricultural productivity in a sustainable manner. This review enhances the perception of the PGPR, relevant outlooks on the various mechanisms of rhizobacteria-mediated promotion of plant growth have been explained in detail with recent research.

***Keywords*:** agro-ecosystems, phytomicrobiome, artificial pesticides, fertilizers, reducing crop yields

1. Introduction

Climate change not only lowers crop yield but also raises the cost of agricultural goods, raising the likelihood of 770 lakh people experiencing food poverty by 2050 [1]. With climate change major rises in global temperature and the appearance of various abiotic factors have a negative impact on agricultural production [2]. Under such circumstances, environmentally friendly innovations and sustainable methods can assist in disrupting this feed-forward circle by enhancing yield and utilization of resources under a variety of more harsh environmental situations [3], with the goal of increasing the production of nutritious food while minimizing unsustainable inputs, regulating harsh weather, and enhancing soil health through sequestering soil carbon, maintaining soil inorganic nutrients and organic matter [2, 4].

Microbes have a wide range of roles in agriculture and food production, including management and nutrient cycling, fermentation and decomposition of organic materials. In 1980, Kloepper and Scroth first introduced the term "PGPR" [5]. PGPR are representative of microbial groupings and have the potential to colonize plant roots and have a

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variety of direct and indirect effects on plant growth, either promoting the growth of plant or protecting it from pests or illnesses [6]. Pseudomonas, Thiobacillus, Serratia, Rhizobium, Bradyrhizobium, Burkholderia, Enterobacter, Bacillus, Streptomyces sp., Azospirillum, Azotobacter, Arthrobacter, Acinetobacter and Frankia are the genera with the majority of genuine PGPR [7]. They engage in a variety of ecologically significant activities and interact with the soil microbiota in both positive and negative ways. By promoting abiotic and biotic stress tolerances and supporting host plants' nutrition, they stimulate plant growth [8].

To reduce the usage of synthetic agricultural chemicals in the production of crops, the usage of effective PGPR biological control agents and biofertilizers is being considered [8-9]. Plant hormones called auxins are essential for regulating plant development and growth in a variety of environmental settings [10]. The synthesis of auxins is acknowledged through PGPR as a key mechanism for promoting plant growth; yet the effectiveness of auxins ultimately relies on the delicate equilibrium of their content, which is the outcome of all the auxin compound sources in the system [11]. PGPR is a trend for the future that has the potential to be a resource for sustainable agriculture and increase the effectiveness of nutrient usage while also ensuring that plants have access to vital nutrients [12]. Therefore, this article will try to shed additional light on the role of PGPR in improving agricultural sustainability and nutrient usage efficiency simultaneously. This information could be extremely useful to those who are worried about agricultural sustainability and environmental conservation.

2. Rhizobacterial types that promote plant growth

PGPR, a varied group of soil bacteria and an important part of soil-plant systems is involved in a complex network of connections in the rhizosphere that influence plant yield and growth [13]. Intracellular plant growth-promoting rhizobacteria (iPGPR) and extracellular plant growth-promoting rhizobacteria (ePGPR) are two different types of rhizobacteria that promote plant growth [14]. GPR is a member of the Rhizobiaceae family, including Bradyrhizobium, Rhizobium, Allorhizobium and Mesorhizobium, endophytes and species of Frankia can work together to mutually fix the nitrogen from the atmosphere with taller plants [15].

In contrast to PGP, which is typically found inside the specific nodule structure of the cells of the root, ePGPR may be found in the gaps between the root cortex cells, rhizoplane, or rhizosphere. *Serratia, Pseudomonas, Micrococcous, Flavobacterium, Erwinia, Chromobacterium, Caulobacter, Burkholderia, Bacillus, Azospirillum, Azotobacter, Arthrobacter* and *Agrobacterium* are among the bacterial genera that belong to ePGPR [16-17].

3. Mechanism of action of PGPR

The processes through which bacteria can affect plant growth vary by species and strains; PGPR can either directly or indirectly affect plant growth [18]. There are 2 ways to promote growth in plants. Rhizobacteria support plant growth either directly through regulating levels of plant hormone, or their capacity to supply nutrients (potassium, phosphorus, nitrogen, and other essential minerals) or indirectly (Figure 1) through reducing the effects of several pathogenic microorganisms on plant development and growth in the form of environmental protectors, biocontrol agents, and root colonizers [19].

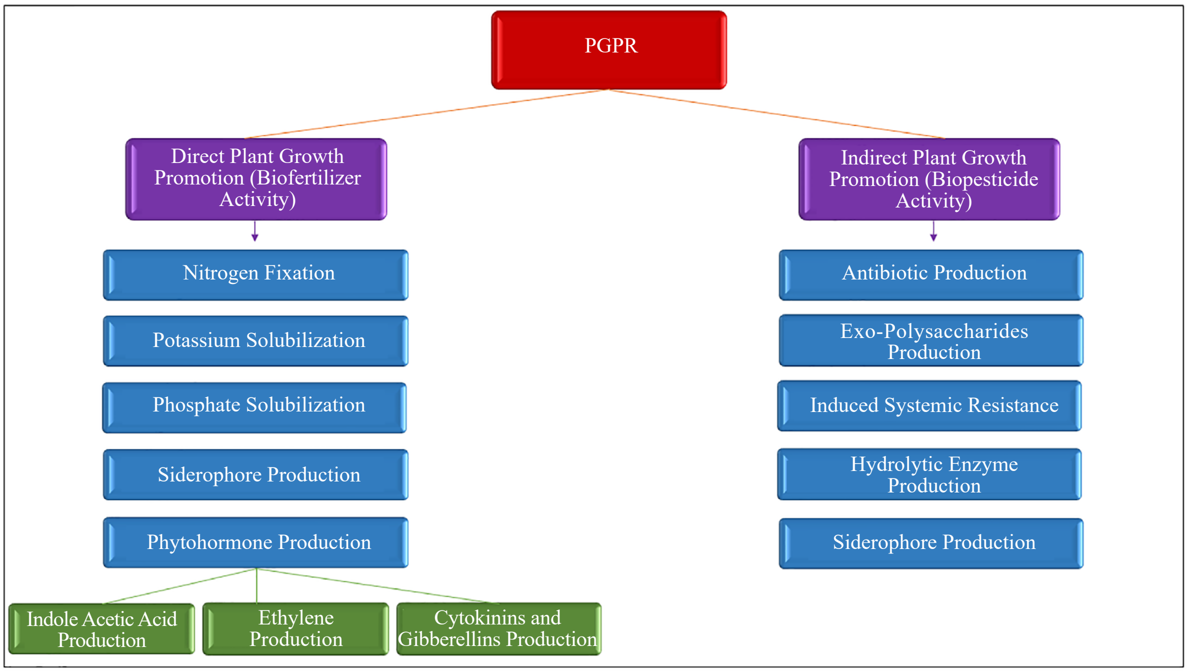

Figure 1. PGPR effect on growth of plants both directly and indirectly

3.1 *Direct mechanisms to promote plant growth*

Rhizobacteria that promote plant growth has direct mechanisms for nutrient availability or nutrient uptake through nitrogen fixation, mineralization of organic compounds, mineral nutrient solubilization and phytohormone synthesis [20].

3.1.1 *Nitrogen fixation*

One of the most crucial components in plant synthesis is nitrogen, because it is an essential part of fatty acids, organic acids, nucleic acids, and peptides, all of which are necessary for the function and structure of all living organisms. Plants are able to use atmospheric nitrogen, because of PGPR's ability to fix nitrogen and transfer it to plants through both symbiotic (mutualistic interaction between bacteria, non-leguminous trees, and legume plants) and non-symbiotic (endophytic and free-living organisms) types of nitrogen-fixing microbes [15, 17, 21]. A mutualistic link exists between the plant and bacterium during the symbiotic fixation of nitrogen. Development of the nodules, where the rhizobia colonizes as intracellular symbionts is the outcome of the complicated interaction among the symbiont and host during the development of the symbiosis [22]. Symbiotic bacteria that act as PGPRs include *Mesorhizobium, Sinorhizobium, Rhizobium, Burkholderia, Herbaspirillum, Azorhizobium, Allorhizobium* and *Bradyrhizobium* with leguminous plants or Frankia with non-leguminous shrubs and trees [23].

Diazotrophs are responsible for non-symbiotic nitrogen-fixing. Diazotrophic bacteria are capable of capturing and fixing nitrogen in soils, which fix nitrogen from the atmosphere into ammonia (Figure 2), the first substrate for the process of nitrification [24]. Nitrifying bacteria, like Nitrobacter sp. or Nitrosomonas sp., convert ammonium into nitrate as the final step in the nitrification process [25]. Free-living bacteria are thought to only supply a tiny portion of the fixed nitrogen needed by the host plant connected with the bacteria [26]. They promote the growth of non-leguminous plants like rice and radish. The genera Gluconacetobacter, cyanobacteria (Nostoc, Anabaena), *Pseudomonas, Enterobacter, Diazotrophicus, Burkholderia, Azospirillum, Acetobacter, Azotobacter* and *Azoarcus* include non-symbiotic nitrogen-fixing rhizospheric bacteria [15].

3.1.2 *Potassium solubilization*

As a macronutrient, potassium is necessary for the growth of plants on a biochemical and physiological level

[27]. The bulk of potassium-containing substances are present in soil in a stable form that is challenging for plants to use [28]. The insoluble form of potassium is solubilized by certain rhizospheric organisms, like potassium solubilizing bacteria (KSB), and released in a form that plants can utilize for their personal production and development. The methods used by PGPR to solubilize potassium include reduction, exchange, acidolysis, organic acid excretion, and chelation [29]. The microbial species engaged in the solubilization of potassium include. *Acidithiobacillus ferrooxidans, Paenibacillus sp., Pseudomonas sp., B. mucilaginosus sp., Burkholderia sp.* and *Bacillus edaphicus* [30]. Additionally, Solanum lycopersicum (tomato) nematicidal activity and development are both positively impacted by the inoculation of potassium-solubilizing bacteria (KSB) [31-32].

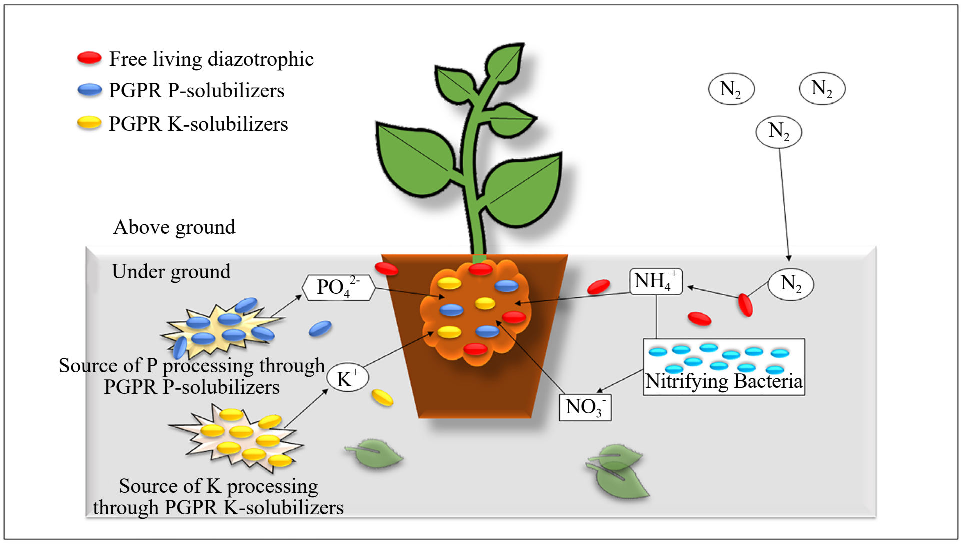

Figure 2. PGPR promote the improvement of potassium (K), phosphorus (P) and nitrogen (N) for plants and soil. PGPR function as P or K solubilizers and releasing P or K in forms that plants may absorb. Nitrogen can be taken from the atmosphere by free living diazotrophic bacteria and then released to plants as nitrate (NO_3^-) or ammonium (NH_4^+)

3.1.3 *Phosphate solubilization*

Phosphorus is the second significant nutrient after nitrogen that limits plant growth, and is widely abundant in soils in both inorganic and organic forms [33]. Phosphate solubilizing bacteria (PSB) have the ability to hydrolyze insoluble inorganic phosphorus into soluble organic phosphorus, which is then utilized as a nutrient through the plants. PGPR in the soil uses a variety of methods to utilize phosphorus that is not available to plants and aid in making it so that plants can absorb it [17]. In general, bacteria employ 2 different methods of phosphate solubilization; 1) through the release the organic acids and altering phosphorus mobility through ionic interactions, and 2) through using phosphatases, which aid in releasing the phosphate groups from organic materials. In general, these mechanisms work better in basic soils [34].

The PGPR has to be put into the soils for it to be efficient and depending on the soil fluctuation or composition, it may occasionally be effective or entirely ineffective [35]. Phosphorus that plants need the most for development and growth exists in the form of inorganic and it becomes accessible to plants through phosphate solubilizing bacteria (PSB) plants inoculated with the phosphate solubilizing bacteria boost yield and growth in plants. Endosymbiotic rhizobium strains and ectorhizospheric *Bacilli* and *Pseudomonas* strains have been examined as excellent phosphate solubilizers in soil bacterial communities [36]. The most important Bacillus strains are *Enterobacter, striata, sircalmous, polymyxa, subtilis, circulans and Megaterium* [37-38]. Mesorhizobium mediterraneum and Mesorhizobium ciceri both nodulating chickpea species, are considered effective phosphate solubilizers [39]. The second-most significant legume in the entire globe, chickpea may nodulate with a variety of rhizobial species to produce root nodules. In many parts of the world, Mesorhizobium ciceri and *Mesorhizobium Mediterranean* were the most common species, but they were excluded from China, where only *Mesorhizobium euxinia* and *Mesorhizobium multiverse* were detected [40].

3.1.4 *Phytohormone production*

Numerous bacteria in the rhizosphere have the ability to synthesize compounds that regulate the growth and development of plants [17]. Naturally occurring chemicals in plant tissues play a regulatory role in growth and development rather than as nutrients. These molecules are referred to as phytohormones or plant growth substances and are often active at extremely low concentrations [41]. Rhizobacteria that promote plant growth accumulate phytohormones like ethylene, gibberellins, cytokinins and auxins that can impact cell proliferation in the root structure through overproducing root hairs and lateral roots, which then results in an increasing water intake and nutrition [42]. According to reports, 80% of organisms found in the rhizosphere of different plants are able to produce and release auxins as secondary metabolites [43].

One of the most prevalent and extensively researched auxins is indole-3-acetic acid (also known as IAA), and a large portion of the scientific literature uses the terms auxin and IAA interchangeably [44]. Cell elongation, differentiation, extension and division are its primary functions. The introduction of indole-3-acetic acid which has been produced through soil bacteria may change the endogenous pool of indole-3-acetic acid in plants, which is why indole-3-acetic acid secreted through rhizobacteria generally affects several plant growth processes [45].

Ten bacterial strains were discovered from soil Acorus calamus rhizospheric soil in the Nagapattinam and Melaiyar districts of Tamil Nadu and were identified as *Azotobacter sp., Pseudomonas sp., Bacillus sp.,* and *Azospirillum sp.* [46]. These underwent indole-3-acetic acid production testing. Pseudomonas accounted for 94% of the indole-3-acetic acid production, followed by *Azospirillum sp.* (80%), *Azotobacter sp.* (65%), and *Bacillus sp.* (40%). Similar to this, indole-3-acetic acid production through *Bacillus* is a trait common to all rhizobacterial isolates [47].

3.1.5 *Siderophore production*

Siderophores are specialized iron chelators that are low molecular weight secondary metabolites developed under low iron stress by PGPR [48-49]. For plants, iron is a crucial nutrient. Because iron functions as a cofactor in several enzymes necessary for vital physiological activities like nitrogen fixation, respiration and photosynthesis, iron shortage manifests as severe metabolic changes [34]. Because iron is frequently found in the environment in the form of the extremely insoluble $Fe3^{+}$ ion, PGPR secrete siderophores to address this issue. Low molecular weight iron-binding protein molecules are known as siderophores. Siderophore is involved in the technique of chelating ferric iron ($Fe3^{+}$) through surroundings [26]. Siderophores, which are released by organisms such as plant cells and microbials, are important metabolites in adapting to surviving in heavy metal-contaminated or metal-limited environments [50].

Siderophore possesses particular sites for iron binding to produce a siderophore complex on the bacterial cell membrane, where ferric is converted to ferrous form and expelled through siderophore under iron-limited conditions for plant absorption [51]. Phyllobacterium strain is a siderophore-producing rhizobacterium that favors strawberry growth and quality [52]. *Rhizobium, Streptomyces sp., Serratia, Pseudomonas, Enterobacter, Burkholderia, Bacillus, Azospirillum, Azotobacter* and *Aeromonas* are among the PGPR that assist in the production of siderophores that transport iron into plant cells and encourage their growth [53].

3.2 *Indirect mechanisms to promote plant growth*

PGPR function as plant growth stimulants in a variety of indirect ways due to their biological control abilities and ability to induce systemic resistance towards phytopathogens. Several characteristics of microorganisms that promote plant growth allow them to biological control a variety of phytopathogens [54]. This includes;

3.2.1 *Antibiotic production*

As an alternative to conventional pesticides, the use of microbe antagonists to control plant diseases in crops for agriculture was suggested. Pathogenic microorganisms are actively suppressed by antibiotic-producing PGPR obtained from the *Pseudomonas* and *Bacillus* genera. Through the production of extracellular compounds that are inhibiting at extremely low concentrations, that bacterium antagonist imposes the prevention of plant pathogens [55]. The *Bacillus* genus of bacteria produces a broad range of antibiotics that are both antifungal and antibacterial. Certain of those substances, such as subbasin, TasA, subtilosin A and subtilin are well recognized and produced from ribosomal origin.

However, other compounds, including lipopeptides, difficidin, bacillaene, rhizocticins, mycobacillin, chlorotetain and bacilysin from the fengycin, surfactin and iturins families are produced through polyketide synthases or/and non-ribosomal peptide synthetases [56]. Pseudomonas sp., an antibiotic-producing 2, 4-diacetyl phloroglucinol (2, 4-DAPG) in soils, has been utilized to biologically control a fungal disease in wheat [57]. In addition to producing antibiotics, many rhizobacteria have the ability to produce hydrogen cyanide (HCN), a volatile substance that is utilized to biologically control the Thielaviopsis basicola-caused black root rot of tobacco [58].

3.2.2 *Exo-polysaccharides production*

Exo-polysaccharide synthesis (EPS), effectively helps bacteria colonize the area surrounding plant roots [59]. PGPR in soil helps remove toxins and pollutants from the water and soil [60]. Bacteria stuck in the exo-polysaccharide layer are protected through an exo-polysaccharide-driven biofilm from harsh environments like radiation, salt and antibiotics [61]. Plant root colonization by EPS-producing bacteria helps in separating insoluble and free phosphorus in soils, providing important nutrients to the plant for proper development and growth, and protecting it against disease attacks. EPS-producing bacteria play several kinds of roles in plant-microbe interactions, including stress resistance, desiccation resistance [62], plant defense response, plant invasion and surface adhesion [63]. Because they function as an active signal molecule during positive interaction and stimulate a defensive mechanism during the infection phase, plant exopolysaccharides developed by PGPR are essential in promoting plant development [64-65].

3.2.3 *Induced systematic resistance*

Plants may develop a state of intensified defense known as induced systematic resistance (ISR) when properly stimulated. There are two types of induced resistance; 1) systemic acquired resistance (SAR) and 2) induced systemic resistance (ISR), which can be distinguished based on the elicitor characteristics and the pathways of regulation involved [66]. The defensive responses ISR and SAR are triggered by compounds termed elicitors that are present or synthesized by pathogens or the PGPR [34]. The main components of SAR, can be triggered through exposure of the plant to non-pathogenic, virulent and avirulent microorganisms and increases the formation of pathogenesis-related proteins (glucanase and chitinase) and salicylic acid [13]. ISR doesn’t require the formation of pathogenesis-related proteins or salicylic acid. However, ISR relies on pathways controlled by ethylene and jasmonate, and those hormones promote the host plants’ protection action towards a wide range of plant pathogenic organisms [45]. Siderophores, flagella, lipopolysaccharides and other bacterial components may also trigger induced systemic resistance [67]. It has been demonstrated that Phytophthora blight on squash produced by Phytophthora capsici can be successfully suppressed by PGPR-mediated induced systemic resistance [68].

3.2.4 *Hydrolytic enzyme production*

Glucan, chitin and cellulose are some of the compounds found in the cell walls of oomycetes and fungi. Therefore, they are the main targets of various lytic enzymes synthesized via PGPR, such as chitinases, cellulases, lipases and 1, 3-glucanases [69]. Rhizobacterial strains that promote plant development may produce a variety of enzymes including proteases, phosphatases, lipases, glucanases, dehydrogenases, etc. [70] these enzymes have hyperparasitic activity, which means they target pathogens by releasing cell wall hydrolases [17]. The pathogen *B. cinerea*, causing grey mold, is killed by the chitinases produced by the rhizospheric bacterium *Bacillus thuringiensis* UM96 [71]. Additional lytic enzymes, including glucanases and cellulases, may also function as antifungal agents. Certain enzymes including cellulases, that are experts in breaking down cellulose or other cell wall polymers, also have a significant impact on a plant’s ability to fight off pathogens [72]. This is because some of these target compounds are found in plant cell walls, which are prone to attack. However, plant tissues are not visibly harmed by PGPR having cellulolytic features [73].

3.2.5 *Siderophore*

A low molecular weight organic molecule that chelates iron is known as a siderophore. Iron is a crucial element for animals, microorganisms, and plants [74]. PGPR that produce siderophore can limit the development of harmful microbes via sequestering $Fe3^{+}$ in the root zone [75]. These siderophores attach to ferric ions to form a siderophore-ferric complex, which then binds to iron-limiting receptors on the bacterial cell surface. The ferric ion is then liberated and active in the cytoplasm as a ferrous ion [17]. Numerous researches revealed the isolation of siderophore-producing bacteria from the rhizosphere that belonged to the *Streptomyces, Serratia, Rhizobium, Pseudomonas* and *Bradyrhizobium* genera [76]. Table 1 shows the PGPR's role in the rhizosphere.

Table 1. Role of PGPR's in the rhizosphere

PGPR	Crop	Mode of action	References
Bacillus sp. LZR216	Arabidopsis	Strengthening auxin responses and enhancing the number and density of lateral roots	[77]
Microbacterium sp., Rhizobium sp.	Pea (Pisum sativum)	Improve the concentration of nitrogen in plants	[78]
Diazotroph, Rhizobium sp.	Rice (Oryza sativa)	Nitrogenase activity and IAA production enhanced rice yield and nutrient uptake	[79]
Stenotrophomonas sp.	Sweet corn	Nitrogen fixation activity enhanced high N, K and P uptake	[80]
Burkholderia sp.	Rice (Oryza sativa L.)	IAA, ACC deaminase improving biochemical and morphological parameters and decreasing stress ethylene	[81]
Rhizobium leguminosarum bv. Viciae	Pea (Pisum sativum L.)	ACC deaminase increased shoot biomass, nodulation, and nutrient uptake	[82]
Pseudomonas fluorescens, Pseudomonas palleroniana, Variovorax paradoxus	Finger millet (Eleusine coracana)	Production of ACC deaminase and enhanced reactive oxygen species (ROS) assisted drought stress tolerance	[83]
Pseudomonas azotoformans FAP5	Wheat (Triticum aestivum)	Biofilm production improved morphological and physiological attributes	[84]
Bacillus velezensis BS89	Strawberry (Fragaria × ananassa Duch.)	Production of higher amounts of IAA, enhanced chlorophyll content in plant leaves and also increased berry yield	[85]
Streptomyces cinereoruber sp., Priestia megaterium sp., Rossellomorea aquimaris sp., Pseudomonas plecoglossicida sp.	Tomato (Solanum lycopersicum L.)	inorganic phosphate solubilization, production of indole acetic acid (IAA), siderophore secretion and increase root length, stem P uptake, leaf P uptake, leaf area	[86]

4. Criteria to choose perfect PGPR

The rhizobacterial species must have the following qualities in order to develop an effective PGPR formulation [87], and those features are listed below.

- Should have highly rhizospheric competency,
- Should be capable of mass multiplication,
- Should have highly competing saprophytic capacity,
- Should exhibit a wider spectrum of activities,
- Should be ecological compatibility with other rhizobacteria that are present,
- Should be safe for the environment,
- Should have the capacity to withstand abiotic stress (desiccation, oxidizing agents, thermal and radiation) [6].

5. Applications of plant growth promoting rhizobacteria

PGPR interaction is essential for our planet's functioning and health as well as for the productivity and growth of plants [17]. *Bacillus* and *Pseudomonas* are the two most significant genera that have been thoroughly researched for antibiosis mechanisms in disease treatment methods [88]. In 2017, bacteria were extracted through the rhizosphere of canola (*Brassica napus L.*) crops cultivated in central fields in Iran to test for the presence of siderophore-producing bacteria. Using a qualitative chrome azurol sulfonate (CAS)-agar assay, it was discovered that 45 different isolates produced siderophore. Ten isolates out of these were chosen for the CAS-liquid test to measure the rate of siderophore production according to the greatest halo diameter/colony diameter ratios. The types of siderophores synthesized by every one of the 10 isolates were identified using a range of biochemical assays. Based on the most significant rates of carboxylate or hydroxamate synthesis, the best isolates were found. The isolates were recognized as *Stenotrophomonas chelatiphaga* LPM-5 (T) and *Micrococcus yunnanensis* YIM 65004 (T) based on 16S ribosomal ribonucleic acid (rRNA) sequence analysis and a variety of phenotypic characteristics and under greenhouse circumstances, the most promising isolates (LPM-5 and YIM 65004) promoted plant development in maize and canola plants. *S. chelatiphaga* and *M. yunnanensis* considerably enhanced weights and iron (Fe) contents of shoot and root when compared to control, demonstrating that these rhizobacteria have positive effects on plant development and growth. The latter is described for the first time from the rhizosphere of a plant (canola). Additionally, the production of siderophores by *S. chelatiphaga* and *M. yunnanensis* was confirmed for the first time [89]. By enhancing the accessibility and absorption of nutrients from a restricted nutrient pool in the soil/rhizosphere, PGPR stimulates the growth of plants [90].

According to the previous study, when employing biofertilizers in rice production, isolates able to produce siderophores offered greater agronomic yields for rice as compared to utilizing 100% chemical fertilizers. Biofertilizer treatment with a dose of 50% chemical fertilizer instructions resulted in a weight of 3.29 grams for 100 grains of dry grain, but a 100% chemical fertilizer treatment resulted in just 2.70 grams [91]. These findings suggest that PGPR, which produces siderophore and phytohormone, might be produced as a possible biofertilizer or bioagent to boost the productivity and growth of upland rice (*Oryza sativa L.*) in arid environmental circumstances [92].

Toxic levels of heavy metals in soil pose a serious threat to all environmental life. The qualities of the soil are changed by heavy metals, and this has a direct or indirect impact on agricultural systems. Therefore, PGPR-assisted bioremediation is an effective, sustainable, and environmentally beneficial way to get rid of heavy metals. A variety of techniques, such as biomineralization, biodegradation, ACC (1-aminocyclopropane-1-caroxylate) deaminase activity, precipitation, biosorption, biotransformation, chelation, siderophores, efflux systems, bioaccumulation processes, are used by PGPR for cleaning the heavy metal contaminated surroundings. These PGPRs have been shown to be useful in bioremediating heavy metal-contaminated soil by increasing plant tolerance to metal stress, improving nutrient availability in soil, altering heavy metal pathways, and synthesizing certain chemical compounds such as siderophores and chelating ions [93].

Cyanobacteria, yeast, and PGPR can significantly enhance the growth, consistency, and general health of crops, including cowpea. In order to determine yield and growth, the three biofertilizers-PGPR (*B. amyloliquefaciens*), cyanobacteria (*N. mucorum*) and yeast (*S. cerevisiae*) were inoculated into the soil where cowpea plants were to be grown. *Saccharomyces cerevisiae* (Y), *Nostoc mucorum* (C) and Bacillus amyloliquefacien (B) were studied individually as well as in 4 different combinations (B + C + Y, C + Y, B + Y and B + C) as integrated biofertilizers on the plant growth parameters, microbial activity of enzymes and yield features of cowpea. For the environmentally friendly production of cowpea, the synergistic effects of microbe inoculation could be a substitute fertilizing strategy. The combined treatment using cyanobacteria, yeast, and *B. amyloliquefaciens* enhanced the photosynthetic pigments of plants cultivated in the treated soils. The soil dehydrogenase activity, seed N, P, and K contents, as well as improvements in all growth traits, were all noticeably improved in soils treated with this mixture. Comparing inoculated plants (B + C + Y) to control plants, inoculated plants significantly increased plant dry weight at 130%, dehydrogenase enzyme activity at 390%, pod length at 68%, chlorophyll at 180%, and dry weight at 190%. One-way Analysis of Variance (ANOVA) was used to examine the data and measure the significance of differences between means. Additionally, a post hoc test (LSD at 0.05 level) was also run. Vascular bundle length expanded at 22.6%, lower and upper epidermal leaf layering increased by 33.5% and 42.4% and the midrib zone thickness increased at 16.6% as a result of the B + C + Y therapy. For increased yields and cowpea production that is safe for the environment, an integrated nutrient management program utilizing biofertilizer is advised [94].

6. Conclusion and future prospects

Higher agricultural yield with enhanced protection of crops and increased fertility of the soil utilizing an environmentally friendly method is essential. The current review highlights the formulation and development of PGPR in the biological stimulation of several plant growth features. The PGPR stimulation mechanism may be direct or indirect. In numerous agricultural crops, the majority of the PGPR strains significantly enhanced root length, plant height, and dry matter production. By playing an essential function in the integrated pest management (IPM) system, PGPR protects both biological resources and natural habitats. PGPR also promotes growth through decreasing phytopathogens that decrease growth and yield. Researchers are starting to gain a much more complex and comprehensive knowledge of the mechanisms used by PGPR to promote plant growth. This knowledge has enabled the usage of PGPR in agriculture. Future prospects might thus involve the chemical fertilizers replacement and the safe maintenance of the ecosystem. Future research will also be beneficial in enhancing the growth conditions of PGPR products, making them non-phytotoxic to crop plants and tolerant of unfavorable environmental conditions, and producing PGPR products with higher yields and lower costs for agricultural farmers.

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Conflict of interest

The authors declare no competing financial interest.

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