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Review Article

# Plant Growth Promoting Rhizobacteria as Biofertilizers: Application in Agricultural Sustainability

**Amirita Rochlani, Amrita Dalwani, NarinaBanoo Shaikh, Nidahurmain Shaikh, Sarita Sharma* and Meenu Saraf S**

*Department of Microbiology and Biotechnology, University of School of Sciences, Gujarat University Ahmedabad, Gujarat, India*

***Corresponding Author:** Sarita Sharma, Department of Microbiology and Biotechnology, University of School of Sciences, Gujarat University Ahmedabad, Gujarat, India.

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## Abstract

The demand for agricultural productivity has increased dramatically as a result of civilization and industrialization. Chemical fertilizers and pesticides increase agricultural yields, but they can degrade soil fertility and quality, posing environmental risks. As a result, the need for environmentally friendly biological agents, such as plant growth promoting rhizobacteria, has skyrocketed in order to improve soil fertility and agricultural operations while also protecting environmental health. The active activity of plant growth promoting rhizobacteria in the rhizosphere, which promotes the growth and development of host plants, has long been known. Plants growing compounds generated by these microbes have a direct or indirect effect on plant physiology, making them valuable agricultural goods in high demand. The plant's resistance power has been increased against biotic and abiotic stress conditions thanks to the PGPR's direct mechanisms (Nitrogen Fixation, Phosphate Solubilization, Phytohormone Production, and Exopolysaccharide Production) and indirect mechanisms (Siderophore Production, Antibiotic Production, HCN Production, Lytic Enzymes Production, Induced Systemic Resistance and Bioremediation). As a result, PGPR as a bio-fertilizer is a good alternative to chemical fertilizers because it is both environmentally friendly and cost-effective. In this review study, we looked at the usage of PGPR as a bio-fertilizer for agriculture sustainability, as well as its direct and indirect effects on plant growth and development.

**Keywords:** PGPR; Rhizosphere; Biofertilizer; Agriculture Sustainability; Biocontrol Agent

## Introduction

In India, about 60.6 percent of land is used for agricultural pursuits by half of the population, making it an Agricultural Country. Soil structure and composition are crucial factors to consider when it comes to agriculture. Nitrogen, phosphorus, potassium, humidity, carbon content, and a variety of edaphic and biological agents all influence soil composition. Chemical fertilizers supply sufficient nitrogen, phosphorous, and other elements to soil but also degrade soil fertility and quality, resulting in soil and environmental contamination. Many researchers have used a variety of scientific methodologies to improve and expand the growth of agriculture, resulting in disease resistance, salt tolerance, xerotolerance, and stress tolerance. The mutualistic link between plants and rhizospheric inoculants is critical because it allows them to survive abiotic challenges, which improves soil fertility and economics. Rhizobacteria that promote plant growth can be defined as a symbiotic relationship between plants and microbes that enhance plant growth and are found in the rhizosphere [10]. Rhizo refers to the roots, while spherical refers to the surrounding environment. The zone of soil that surrounds a plant's root system is known as the rhizosphere. There are no defined edges in the zone, which is around 1mm wide. Rhizobacteria are a type of bacteria found in the rhizosphere that can form a root's environment [24]. The rhizosphere's diverse microbial communities allow the development of microorganisms that can boost plant growth under abiotic circumstances through direct and indirect mechanisms. Although the root gives the plant mechanical strength and aids in nutrition and water intake, it also secretes a range of chemicals. These chemical substances released by plant roots entice large microbial colonies, and these chemical compounds are known as root exudates. Root exudates modify the chemical and physical properties of soil, which regulates the makeup of soil microbial communities at the root surface. Soil microbial communities are difficult to distinguish due to their great phenotypic and genotypic diversity [21]. The bulk of cells in the soil's upper layer are unculturable, with around $10^9$ cells per gram of soil. The percentage of these cells that have been cultivated and thoroughly researched is minimal, about 5%. Microbial populations discovered in the vicinity of these roots include Bacteria, Fungi, Yeast, and Protozoa. Few of them are free-living, and some of them have symbiotic relationships with a variety of plants [21]. Microorganisms and plant interactions can have a positive, negative, or neutral influence on plants. Microorganisms can have a variety of effects, depending on the soil conditions. To research microbial diversity, a variety of cultivation-dependent and cultivation-independent techniques are applied [1]. Both mechanisms have their own set of advantages and disadvantages [21].

**Figure 1:** Plant-Microbe interaction (Rhizoshpere) (image created by PP in MS Office 365).

The rhizosphere is composed of 3 constituents:

- The Rhizosphere (soil)
- The Rhizoplane and
- The roots.

The rhizoplane is the root surface that is firmly linked to soil particles and is surrounded by microorganisms [6]. Bacteria concentrations in the rhizosphere are 10–1000 times higher than in bulk soil, but relatively low in lab media.

In the past years more attention has been paid to PGPR for the upgradation of soil and enhancement of plant growth via different methods and replacement of chemical fertilizers. A thorough knowledge is required of PGPR and their interactivity with the biotic and abiotic factors is very much crucial in energy generating processes and bioremediation operations [36]. PGPR works better over chemical fertilizers as they are environmentally friendly, also economically viable and best for the soil management practices for attaining more agricultural sustainability and consequently fecundity of soil. Here, we have discussed various mechanisms by which PGPR can be used as an effective tool to achieve sustainable development in agriculture and to improve soil fertility.

## Plant growth-promoting rhizobacteria

The discovery of microorganisms (1683) was credited to the father of microbiology (Anton Van Leeuwenhoek). However, the capacity of these microbes to serve as a plant growth booster has been exploited for centuries. Bacterial variety is abundant in soil, and they play an important role in the operation of terrestrial ecosystem processes. Various microorganisms and leguminous plants work together to improve soil quality and fecundity through symbiotic relationships. Plant growth promoting rhizobacteria was the name given to these beneficial bacteria by Kloepper and Schroth (1981) [24].

## PGPR variants

### There are two types of PGPR present in rhizosphere [29]

- IPGPR (Intracellular plant growth promoting rhizobacteria): IPGPR is found in the root cell's modular structure. For instance, *Frankia* and *endophyte*s work together to fix nitrogen.
- EPGPR (Extracellular plant growth promoting rhizobacteria): EPGPR is found in the root cortex cells rhizosphere (rhizoplane) or intracellular spaces. *Agrobacterium, Caulobacterium, Flavobacterium, Pseudomonas, Serratia,* and other bacteria are examples [18].

In nature, Gram-Negative rod-shaped bacteria are predominantly rhizobacteria, whereas Gram-positive bacterial proportion (rod, cocci) is minimal in comparison to gram-negative bacteria. Because they are a key part of soil nutrient cycling and plant growth promoting activities, the *Actinomycetes* group of bacteria is also implicated in rhizosphere microbial populations. *Micromonospora* sp, *Streptomyces* sp, and *Streptosporangium* sp, which are some of the best identified in the rhizosphere [14], are examples of *Actinomycetes* that operate as plant growth promoting microbes. *Streptomyces* acts as a PGPR in *Pinus taeda*, and has been utilised to control pathogenic fungal infections like Pine Rot. *Actinomycetes* in the soil produce a variety of antibacterial compounds. The effects of *Bacillus subtilis* strains on phytopathogens are investigated. In a wide range of root zone temperatures, PGPR can promote nitrogen fixation and nodulation. Furthermore, utilising these PGPRs as biofertilizers is an ongoing study topic. When in a connection with host plants, PGPR is best described as a vital member of the rhizosphere network that enhances their growth and development. These bacteria can help enhance economic production, soil fertility, and ecosystem stability by responding to stressful situations. PGPR has been widely utilised to increase agricultural and horticultural diversity. They have the ability to turn infertile, unproductive ground into arable and productive land. Rhizobacteria and growing plants have primarily three types of linkages (neutral, positive, and negative) [7].

- **Neutral Consequences:** There are no detectable effects on the host's growth and development as a result of the relationship.
- **Detrimental Effects:** The synthesis of fatal chemicals by phytopathogenic bacteria, such as hydrogen cyanide and ethylene, has a negative impact on plant growth and development.
- **Positive Effects:** There are two types of positive effects.

PGPR promotes plant development in both direct and indirect ways. These include nitrogen fixation, enhancing overall plant biochemistry, combating various biotic and abiotic stress situations, and creating enzymes to manage plant diseases by offering resistance to a variety of phytopathogens through a variety of mechanisms.

The activity of PGPR varies depending on the type of host plant [32,45].

## Mechanism of action of plant growth promoting rhizobacteria

Plant growth rhizobacteria are able to perform various mechanisms in order to improve plant growth and development and eventually lead to the sustainable agricultural practices. Direct mechanisms of these rhizospheric microorganisms can improve plant growth by enhancing the uptake of nutrients via nitrogen fixation, solubilization of phosphate, production of phytohormones and exopolysaccharide production which results in sustainable and eco-friendly prespective of agri-science. These microbes also indirectly involve in the protection of plants due to the production of antibiotics, hydrogen cyanide, siderophores and other biocontrol agents. Therefore, plant growth promotion by plant growth rhizobacteria is an important and innocuous way in agriculture [36].

### Direct mechanisms

PGPR enhance the plant growth and development directly by facilitating nutrient uptake, by nutrient solubilization like of phosphate and potassium, exopolysccharide and phytohormones production, and fixation of Nitrogen [9]. The mechanisms as mentioned directly affects the plant growth but differ according to the plant and microbes involved in it. In the presence of pgpr, increase in individual ion fluxes at the root surface help in direct enrichment of nutrient uptake by plants (Figure 2).

### Improve minerals uptake

The addition of PGPR has an impact on overall plant physiology by affecting the chemical and physical features of the soil, as well as the rhizospheric microorganisms that live in that region. The addition of PGPR, which stimulates proton-pump ATPase, boosted the plant's mineral absorption. Mineral uptake by plants was reported to be enhanced when inoculants or rhizobacteria were applied. These minerals included calcium, phosphorus, iron, copper, zinc, and magnesium. The PGPRs in the rhizosphere create a drop in pH in the soil and plants, resulting in the creation of organic acid, which causes mineral uptake by crop plants [44]. PGPR has been shown in numerous studies to improve the availability of minerals for plants. The important premise in aiding the transfer of such minerals is the solubilization of inaccessible forms of minerals.

### PGPR as nitrogen fixers

Nitrogen (N), a critical component of all life forms, is a vital ingredient for plant growth. Because it affects the composition of nucleotides, membrane lipids, and amino acids, it is an important component. Nitrogen fixation by biological methods is an important microbiological function for supporting life on earth. Photosynthesis is used by photosynthetic bacteria to carry out this process. Nitrogen fixation is the process of producing ammonia from atmospheric nitrogen, which is catalysed by the enzyme nitrogenase [13]. Many PGPR species can fix nitrogen and exhibit significant results, hence research on nitrogen fixation has been ongoing for many years. Many bacterial taxa, such as *Rhizobia*, have been identified that may fix nitrogen mutualistically within plant nodules. Frankia *(Actinobacteria)* can associate with many plant groups and *Alpha-proteobacteria* lives in symbiosis with legume plants. *Cyanobacteria* are also one of the most important nitrogen-fixing bacteria, coexisting with a wide variety of higher and lower plan. The term "associative symbiosis" refers to a relationship between two separate species or biological systems, which can be mutually beneficial or not required to perform certain activities.

### Nitrogen fixation process

As previously stated, nitrogenase converts atmospheric nitrogen to ammonia [13]. Nitrogenase is an oxygen-sensitive enzyme that can be irreversibly inactivated. Nitrogen fixation is accomplished through the hydrolysis of 16 ATP (energy currencies). Nitrogen fixation can be divided into two categories:

- Nitrogen fixation through symbiotic relationships
- Nitrogen fixation through non-symbiotic relationships.

The symbiotic nitrogen fixation process is thought to be more essential than the non-symbiotic nitrogen fixation process because a large amount of nitrogen may be fixed symbiotically. Various genera, such as *Azospirillum, Enterobacter*, and *Pseudomonas,* carry out the non-symbiotic nitrogen fixation process by stimulating the growth of non-leguminous plants [9]. Whereas, in the case of symbiotic nitrogen fixation through inter-relationships with legume plants, *Rhizobium, Sinorhizobium*, and other bacteria are involved. Nitrogen reduction is a difficult procedure that is carried out as follows:

$$N_2 + 16Mg\,ATP + 8^{e-} + 8^{H+} \text{----}\rightarrow 2NH_3 + H_2 + 16\,Mg\,ADP + 16\,Pi.$$

Nitrogen fixation is carried out by the gene (nif), which can activate iron proteins, contribute an electron, manufacture of the iron-molybdenum cofactor, and other genes that regulate enzyme activity. When nitrogen-fixing PGPR is applied to an agricultural field, it can improve plant growth and development, regulate nitrogen levels in the soil, and manage diseases (protection from pathogens) [29]. They have the potential to be utilized as a biological fertilizer.

### Regulators of plant growth

Plant growth regulators are organic chemicals that can promote, inhibit, or change plant growth and development at very low concentrations (approximately 1 mM). These organic compounds can also be produced by PGPR. Auxin, cytokinin, gibberellins, ethylene, abscisic acid, and brassinosteroids are a collection of plant regulators that the root cell can multiply by producing an excess of lateral roots [22,48]. The most important auxin is IAA (Indole -3 Acetic acid), which belongs to a group of hormones.

### Solubilization of phosphate

Phosphorus is the second most important nutrient for plants after nitrogen. Phosphorus occurs naturally in the soil in an inorganic form, making it one of the most important growth-limiting variables in agricultural systems. As a result, it is necessary to apply or add a biological agent capable of converting inorganic/insoluble phosphorus to a soluble form. Plants may easily assimilate this type of phosphorus by converting insoluble phosphorus complex into soluble simple phosphorus with the help of rhizobacteria [20]. Phosphorus is generally present in healthy soil at 0.118 mg/dl, while plants require 0.3393 mg/dl for product growth and development [20]. Among the different techniques of Plant Growth Promotion by bacteria, inorganic phosphate solubilization is extremely important in commercial plants. Plants use the orthophosphate form of phosphorus that rhizobacteria make available. The two forms of phosphorus that are only absorbed by plants are monobasic ($H_2PO_4$) and dibasic ($HPO_4^{-2}$) [25]. Phosphate solubilizers include rhizobacteria such as *Agrobacterium, Flavobacterium, Pseudomonas, Mycobacterium*, and *Bacillus*. Some of the probable phosphate solubilizers found in chickpea nodules include *Mesorhizobium ciceri* and *Mesorhizobium mediterranean*. Mineralization of organic phosphorus compounds can be carried by enzymes such as phosphatase, phytase [26]. Phosphatase enzymes can operate in both acidic and neutral rhizospheric soil pH. Rhizobium has been found to have a high amount of acid phosphatase activity.

### Solubilization of phosphate mechanism

Phosphate solubilizing bacteria use a variety of methods to convert insoluble to soluble forms. Microorganisms produce a variety of organic acids that can chelate out divalent cations such as the $Ca^{+2}$ as well as phosphates. Phosphate is released when organic acids create soluble complexes with metal ions that are strongly connected with insoluble phosphorus [26].

### Exopolysaccharide production

Exopolysaccharide (EPS) is a type of extracellular matrix that can be either a firmly bonded capsule or a freely produced slime layer. PGPR creates EPS, which helps plants develop even in dry soil by maintaining a high moisture content in the soil [32]. Under adverse situations such as drought, EPS has a positive effect on plant growth. By creating EPS, PGPR creates a protective sheath or biofilm around the plant's roots, which protects them from desiccation. They become adhered to surfaces that have excess moisture with the help of EPS [32]. EPS maintains the rhizobium biofilm and ensures that it functions properly. *Rhizobium* sp, *Enterobacter cloacae, Bacillus pretences, Azotobacter vinelandii*, and other PGPR creates EPS [26]. As a result, EPS is directly responsible for the host plants survival in the face of abiotic stress [40].

### Indirect mechanisms

PGPR promotes plant growth indirectly by reducing the negative impacts of pathogenic microorganisms. They contribute to the host's defense power by triggering the synthesis of hostile chemicals [46]. This strategy indirectly promotes plant growth by preventing phytopathogens and their harmful effects, as well as assisting the plant in growing under diverse abiotic conditions. They aid plant growth by creating enzymes, opposing chemicals such as antibiotics, and enhancing host resistance power. Indirect processes include the formation of siderophores, EPS, and cyanides, all of which act as plant pathogen antagonists (Figure 2) [40,42].

**Figure 2:** Direct and Indirect mechanisms of plant growth promoting rhizobacteria (image created by PP in MS Office 365 ProPlus, PowerPoint).

### Siderophore production

In an iron-deficient environment, microorganisms make small organic compounds called siderophores, which aid in iron grabbing. Siderophores have been the subject of a lot of research in the last ten years because of their unique ability to collect iron metal cations. *Pseudomonas* species which acts as a PGPR utilizes siderophores produced by microorganisms in the rhizosphere to meet their ions requirements [20]. Especially, *Pseudomonas putida*, in particular, exploits siderophores produced by other microorganisms to enhance the amount of iron available. A powerful siderophore like ferric-siderophore complex plays a vital role in iron uptake by plants when other metals such as nickel and cadmium are present. Because it can create siderophore, PGPR is a valuable asset that provides the required amount of iron [20]. PGPR, which makes siderophores has been shown to be a possible biocontrol agent for preventing plant diseases [17]. Between 12 and 24 ppm of iron is available for plant absorption. The use of iron chelates/salts, modification of soil pH, application of organic matter to soil devoid of accessible iron, and application of cultivars with the ability to uptake iron from the soil are all examples of soil management and implantation that aims to nurture these values and optimize iron deficiency. However, this strategy appears to be ineffective and costly. The ability of PGPR to capture iron through their siderophores and make it available to plants appears to be the most effective technique for meeting their iron intake demand [39,49].

### Production of HCN (hydrogen cyanide)

HCN is a biological control agent and one of the most important chemical molecules produced by rhizobacteria that promote plant growth [26]. The secondary metabolite produced during the early stationary phase is hydrogen cyanide. There is no growth, energy storage, or main metabolism involved. Cyanide is produced by a variety of bacteria, fungus, algae, and plants. Because cyanide is poisonous, it colonises in plant root sections and makes it difficult for weeds to survive, making it an effective biocontrol weed agent [36]. *Bacillus* and *Pseudomonas* species produce HCN in large quantities (88.89 percent) [1]. Because cyanide is poisonous, inoculating plants with HCN-producing PGPR has no negative consequences. The HCN-producing PGPR is only found in the roots of their host plants. HCN kills cells through interfering with the electron transport chain (ETC) and energy supply.

### Production of antibiotics

There is a lot of competition for resources among bacteria in the natural world. As a result, the release of antibiotics permits these PGPR species to compete effectively. PGPR can kill pathogens in plants, however overuse of antibiotic-producing PGPR strains can cause pathogenic strains to become resistant [23]. Because of their broad-spectrum activity, fluorescent *Pseudomonas* species are usually used against plant diseases. Antibiotics stimulate ISR (Induced Systematic Resistance) genes in plants, making antibiotics primary role in plant disease management [39].

### Production of lytic enzymes

PGPR promotes plant growth by stimulating the production of metabolites that regulate phytopathogenic agents. PGPR produces enzymes such chitinase, SOD (superoxide dismutase), and ACC (1-aminocyclopropane-1-carboxylic acid) deaminase, which aid in the destruction of pathogen cell walls [16]. The fungal cell wall is made up of chitin and beta 1-4 N-acetylglucosamine, and the PGPR bacteria produces enzymes called beta 1-3 glucanase and chitinase that cause cell wall rupture and so restrict fungal development. *Fusarium oxysporum* and *Fusarium udum* cause *fusarium wilt* by producing enzymes such as chitinase and beta-glucanases, which are produced by PGPR such as *Pseudomonas fluorescence* LPK2 [35].

### Induced systematic resistance

In addition to increasing mineral intake and improving general plant physiology, rhizospheric inoculants can also strengthen plant defense systems, making the plant resistant to a variety of phytopathogens. Plants, for example, respond to biotic stressors such as diseases and insects [28]. Some systemic responses spread to other parts of the plant, far from the injured organ, triggering defensive systems throughout the plant. Induced resistance is a physiological state in which the crop plant's defensive efficacy is improved as a result of biological or chemical means, which helps protect plant tissues that were not exposed to the initial attack from future attacks [50]. Induced resistance can be triggered by rhizospheric inoculants colonisation or diseases such as insects or herbivores [33]. When pathogens enter defensive mechanisms are activated, such as the creation and activation of defense enzymes such as phytase, peroxidases, chitinase, beta 1-3 glucanase, superoxide dismutase, and a few proteinase inhibitors. ISR (induced systemic resistance) is a plant defense mechanism that helps the plant avoid illness. For a specific pathogen, ISR is not very specific. Within the plant, ethylene hormone transmission causes induced systemic resistance, which maintains the defensive mechanism active against several plant diseases [38]. Lactones, lipopolysaccharide, siderophores, acetoin, and butanediol are some of the structural components of the bacterial cell that can cause ISR. As PGPR is isolated from the roots of a bean plant, it induces resistance, resulting in a significant decrease in PDI (percent disease incidence) and viral concentration when compared to non-bacteria plants [12].

### Tolerant to abiotic stress

Any element that hinders a plant's growth is referred to as stress. The formation of free radicals and highly reactive oxygen species increases in response to many types of stress [11]. Overproduction of these species oxidises photosynthetic pigments, lipids, proteins, and other plant-like components, causing harm. PGPR research has only been conducted on agricultural plants. Under abiotic stress circumstances, leaf water status has been improved with the use of PGPR [2,31,40,43,44]. PGPR also aids in the neutralisation of adverse effects on plants by scavenging the cadmium ion that causes the problem [41]. PGPR has proven to be good scavengers and aid in strengthening resistance to abiotic stress by creating ROS - Scavenging enzyme [15,19]. Plants can be stressed by pathogens such as bacteria, viruses, fungus, insects, and nematodes [26]. As a result of their impact, crop yields and thus production are reduced. According to sources, the negative effects of one or more phytopathogenic organisms account for around 15% of global loss [42].

PGPR strains such as *Paenibacillus polymyxa* B2, B3, B4, *Bacillus amyloliquefaciens* HYD-B17, *Bacillus thuringiensis*, and *Bacillus subtilis* RMPB44 can help with issues such as ecosystem nutrient cycling, co-evolution, and horticulture plant health [31].

### Biofertilizers

The symbiotic interaction between microorganisms and fungi has been studied extensively, leading to the coining of the terms "bioinoculant" and "biofertilizer" [8]. Biofertilizers are living microorganisms that contribute to plant growth and development by increasing the availability of critical nutrients to the plant when inoculated to seeds, plant surfaces, or soil [34]. These vital nutrients are classified as macronutrients (N, P, K, Ca, Mg, S) and micronutrients (Zn, Fe, Cu, Mo, Mn, B, and Cl), with N, P, and K being particularly crucial in helping plants endure stress situations such as drought, cold, and diseases. Chemical fertilizers are commonly employed in farm management nowadays [3]. Chemical fertilizers are man-made compounds that are applied to crops in order to increase their yield and production [37]. However, these chemical fertilizers are not only expensive, but they also pose a health risk. As a result of the search for environmentally appropriate alternatives, biofertilizers (microbial products) were developed. The health of the soil can be improved as a result of their microbial activity, and they also give necessary nutrients to plants. When biological fertilizers are inoculated, they begin to proliferate and participate in nutrient cycle, benefiting plants [27]. To reduce the use of chemical synthetic fertilizers, effective plant growth-promoting rhizobacteria (PGPR) as biofertilizers are more beneficial, eco-friendly, non-destructive, and non-virulent to the host plant [5,47]. Biofertilizers are microbial cultures that are cost-effective, easy to use, and provide higher growth rates and yields than organic and chemical fertilizers [4]. Phosphate solubilization, nitrogen fixation, and the generation of plant development compounds are all helpful actions performed by bacteria utilized as biofertilizers [25,30]. Plants have hostile effects towards diverse phytopathogens as a result of the presence of these bacteria [8]. At the industrial level, a wide range of microorganisms can be utilized as biological fertilizers, depending on their capabilities, such as supplying nutrients to plants and functioning as natural pest deterrents.

The following traits should be present in the optimal strain

- It must be capable of standing in the presence of an already existing bacterial population.
- It must be able to withstand environmental conditions like temperature, radiation, drought, and other abiotic factors, among other things.
- It must be compatible with other microorganisms.
- Their actions and activities must be diverse.
- It must be capable of promoting the host plant's growth and development.
- It must be environmentally friendly, as it should not impair the environment's health.
- They must be able to interact with the host plant, enhancing the flow of nutrients directly (N, P, and Fe).
- They should promote plant fitness and provide stress protection.
- They must be able to reproduce in the rhizosphere [51].

## Conclusion

Chemical fertilizers have been widely utilized in agricultural techniques for several decades, however the long-term impacts of these fertilizers on our surrounding environment, including soil, human health, and so on, are rather concerning. These negative repercussions include soil contamination, a deteriorating climatic environment, and land misuse, all of which wreak havoc on soil fertility and agricultural methods. To solve these issues, one must use scientific knowledge to recognize the interaction of soil with microbes and their impact on plant growth. We can protect soil and plant production while simultaneously increasing output by doing so. Using beneficial PGPR consortia, we can create biofertilizers, bioherbicides, and bioinsecticides to replace hazardous chemical fertilisers. PGPR is an important part of the IPM (Integrated Pest Management System). The direct and indirect mechanisms of PGPR, such as nitrogen fixation, phosphate solubilization, exopolysaccharide production, phytohormone production, HCN production, lytic enzyme production, antibiotic production, induced system resistance, and siderophore production, are increasing plant growth, yield, and nutrient uptake. More research on specialized rhizospheric inoculants and microbial colonization in multidisciplinary fields that involve applications in nanotechnology, agrotechnology, material science, and merging functional approaches can result in novel formulations with better and more efficient results.

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## Conflicts of Interest

We declare that there are no conflicts of interest.

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