Vidhyayana - ISSN 2454-8596
An International Multidisciplinary Peer-Reviewed E-Journal
www.vidhyayanaejournal.org
Indexed in: Crossref, ROAD & Google Scholar

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# The Role of Plant Growth Promoting Rhizobacteria in Sustainable Agriculture

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**Abstract:**

Rhizosheric bacteria with several abilities related to plant growth and health have been denominated Plant Growth-Promoting Rhizobacteria (PGPR). PGPR promote plant growth through several modes of action, be it directly or indirectly. The benefits provided by these bacteria can include increased nutrient availability, phytohormone production, shoot and root development, protection against several phytopathogens, and reduced diseases. Additionally, PGPR can help plants to withstand abiotic stresses such as salinity and drought and produce enzymes that detoxify plants from heavy metals. PGPR have become an important strategy in sustainable agriculture due to the possibility of reducing synthetic fertilizers and pesticides, promoting plant growth and health, and enhancing soil quality. There are many studies related to PGPR in the literature. However, this review highlights the studies that used PGPR for sustainable production in a practical way, making it possible to reduce the use of fertilizers such as phosphorus and nitrogen and fungicides, and to improve nutrient uptake. This review addresses topics such as unconventional fertilizers, seed microbiome for rhizospheric colonization, rhizospheric microorganisms, nitrogen fixation for reducing chemical fertilizers, phosphorus solubilizing and mineralizing, and siderophore and phytohormone production for reducing the use of fungicides and pesticides for sustainable agriculture.

**Keywords:** Food Production; Nitrogen Fixation; Phosphorus Solubilization; Siderophores

## 1. Introduction

Plant growth-promoting rhizobacteria (PGPR) are a group of beneficial, free-living bacteria that establish symbiotic relationships with plant roots, leading to enhanced plant growth. These bacteria contribute to plant development through various mechanisms, such as metabolic activities like phosphate solubilization, hormone production, and nitrogen fixation. They can also directly impact plant metabolism, improving water and mineral uptake, promoting root growth, increasing enzymatic activity, and supporting the actions of other beneficial microorganisms. In addition, PGPR play a vital role in plant protection by competing with pathogens for essential nutrients, producing antimicrobial compounds, generating enzymes that break down fungal cell walls, and triggering systemic responses in host plants. Moreover, PGPR can help plants thrive even in adverse environmental conditions by enhancing their overall fitness, stress tolerance, and pollution remediation capabilities. A deeper understanding of the specific bacterial traits responsible for promoting plant growth can inspire innovative solutions for harnessing the potential of PGPR in highly dynamic environmental and climatic conditions.

## 2. The Use of Unconventional Fertilizers

The agricultural industry faces a persistent challenge in increasing both the quantity and quality of agricultural production, while also enhancing the efficiency of processing and storage. To achieve these goals, there is a growing need to optimize the use of mineral fertilizers in plant cultivation. It is widely recognized that the application of mineral fertilizers according to optimal standards is pivotal for improving soil quality, enhancing fertility, and ultimately boosting crop productivity. Many agronomic practices must be adapted and fine-tuned to maximize food production yields and quality. Consequently, agronomic strategies need to be continuously revised and improved.

In recent years, many researchers have turned to biofertilizers as a means to mitigate the environmental pollution associated with mineral fertilizers and to reduce production costs.

The utilization of waste materials for the creation of liquid fertilizers, with properties akin to traditional mineral fertilizers, holds great promise for sustainable agriculture. This approach not only conserves natural resources but also aligns with the principles of a circular economy.

This review explores the challenges faced by the fertilizer industry in its quest to provide plant nutrients through more energy-efficient and eco-friendly methods. It introduces the concept of producing liquid fertilizers from waste materials that possess fertilizing properties, thereby diminishing the strain on natural resources and fostering a circular economy. Furthermore, the review sheds light on the current regulatory landscape in Poland and the European Union, which encourages the adoption of circular economy practices and the extraction of valuable plant nutrients from organic waste and recycled materials.

The review delves into the various waste materials used as substrates for fertilizer production and their essential chemical properties conducive to plant growth and development. It underscores the importance of this research direction and the need to explore additional waste categories that can be repurposed within the framework of a circular economy.

In a separate study, an investigation was conducted to assess the impact of a novel organic-inorganic compound fertilizer on fragrant rice. This innovative fertilizer formulation comprised organic matter, urea, superphosphate, potassium chloride, zinc sulfate, and lanthanum chloride. Over the course of four years, three treatments were compared: no fertilizer, traditional fertilizer, and the new organic-inorganic compound fertilizer. The results demonstrated that the new fertilizer significantly enhanced grain yield, effective panicle number, seed-setting rate, chlorophyll content, net photosynthetic rate, aboveground biomass, and the production of 2-acetyl-1-pyrroline in fragrant rice when compared to other treatments. This study suggests that the new fertilizer has the potential to substantially increase both yield and grain quality in fragrant rice production.

Additionally, there is a discussion of the advantages of employing plant growth-promoting microorganisms (PGPMs) in hydroponics and vertical farming systems. The controlled environment within these systems offers an optimal setting for harnessing the benefits of PGPMs. The authors recommend a synchronized approach involving the application of PGPMs with a biostimulant extract to the hydroponic medium, along with pre-treating seeds or seedlings with a microbial suspension in aquaponic and aeroponic systems. Notably, the global market for vertical farming is projected to surpass USD 10.02 billion by 2027, driven by factors such as efficient space utilization, reduced water consumption, decreased pesticide usage, and the implementation of user-friendly technology for environmental control and harvesting.

## 3. Seed Microbiome for Rhizospheric Colonization

Seeds are known to harbor various endophytic microorganisms, with a particular emphasis on bacteria. These microorganisms are intentionally chosen by the plant because of the multitude of advantages they offer. Initially, they establish themselves in the rhizosphere, then progress to become endophytes within the plant's tissues, eventually finding their way into the seeds. It is worth noting that these endophytes play a vital role in the germination, preservation, and growth of seeds, and they are commonly found in the surrounding soil. The findings strongly indicate that plants purposefully select these microorganisms from the rhizosphere, recognizing the benefits they provide, ensuring their presence when the seeds are sown. The colonization of endophytes within seed tissues is contingent on varying chemical compositions. Additionally, the plant's defense mechanisms prevent the microorganisms from reaching high population densities within the plant organ, as excessive growth could lead to an infection through quorum sensing.

Endophytic seeds exhibit vertical transmission from the roots to the stem, forming a close and intricate interaction with the developing embryo during germination. These endophytic seeds play a crucial role in fostering seedling growth and development through various mechanisms, including the solubilization of essential nutrients like potassium and phosphorus, the promotion of growth-related hormones such as cytokinin and auxin, and the nitrogen-fixing capacity. Furthermore, endophytic seeds confer substantial benefits to plants, enhancing their resistance to both biotic and abiotic stressors and contributing to overall plant fitness.

In a study involving the isolation of twenty-three microbial endophytes, predominantly bacteria, from maize seeds, a remarkable 70% of these isolates demonstrated the synthesis of auxin, while 74% exhibited a spectrum of capabilities, notably phosphate solubilization.

Notably, all the isolates displayed the vital ability to fix nitrogen. Additionally, a substantial proportion of these isolates exhibited antagonistic properties against phytopathogenic fungi such as Fusarium sp. and Rhizoctonia solani, underscoring their potential for use in biocontrol strategies.

Within the context of seed rice, previously unreported bacterial strains were identified, including Bacillus sp., Citrobacter sp., Flavobacterium sp., and Pantoa sp. Among these, Citrobacter proved to be the most proficient in producing indole acetic acid (IAA), gibberellin, and hydrogen cyanide (HCN), while Pantoa excelled in phosphate and potassium solubilization as well as ammonia production. These findings underscore the pivotal role of seed endophytes in supporting plant growth and development while bolstering the plants' defenses against various phytopathogens, both fungal and bacterial, thus contributing to sustainable agricultural practices.

## 4. Rhizospheric Microorganisms

The region surrounding plant roots is commonly referred to as the rhizosphere. Plants engage in photosynthesis, during which they allocate approximately 10 to 40% of their photosynthetic products to the rhizosphere through a process known as rhizodeposition. This rhizodeposition enriches the rhizospheric soil with nutrients, amino acids, and energy-rich organic compounds like carbohydrates, effectively fertilizing it. This fertilization of the rhizosphere has a substantial impact on the nearby soil microbiota, leading to changes in its composition.

Plants actively influence the microorganisms within the rhizosphere through a combination of physiological factors that regulate interactions between plants and microorganisms, as well as the composition of compounds they release. The composition of microorganisms within the root system is a carefully selected one, and the establishment of the root microbiome occurs in two distinct stages. The first stage involves the colonization of the rhizosphere, which is achieved by a subset of microorganisms originating from nonrhizosphere soil and the bulk soil. In the second stage, a specific group of microorganisms from the rhizosphere migrates to colonize the phyllosphere and endosphere regions.

Numerous factors influence the plant holobionts, shaping the composition of their microbiomes. A holobiont is the combination of a plant's genome and the genome of its associated microbiome. Interestingly, even when plants are grown under different conditions, they may host the same groups of microorganisms. These persistent microorganisms are collectively known as the core microbiome, which is shaped by factors shared across various plant species. Conversely, plant-specific factors lead to associations with microorganisms that are not part of the core microbiome.

Microorganisms in the rhizosphere, the soil region influenced by plant roots, derive nutrients and energy from substances released by the roots, such as rhizodeposition and border cells. The larger the volume of a plant's root system, the more substantial the deposition and release of these molecules, thereby increasing the availability of energy and nutrients to the microbial population in the rhizosphere. In contrast, a more developed plant shoot enhances photosynthetic efficiency, resulting in the production of energy molecules. These microorganisms are often referred to as phytostimulants as they synthesize phytohormones, benefiting themselves while promoting both shoot and root development. Phytohormones play a crucial role in enhancing the survival of these microorganisms by countering the plant's defense mechanisms against them.

PGPR (Plant Growth-Promoting Rhizobacteria) can also facilitate plant growth through the induction of systemic resistance (ISR) and systemic acquired resistance (SAR) in plants. These are innate defense mechanisms employed by plants to safeguard themselves against pathogenic threats such as bacteria, viruses, and fungi. ISR is initiated by non-pathogenic microorganisms and initiates in the root, eventually extending to the shoot. This defensive response relies on ethylene and jasmonic acid signaling within the plant. On the other hand, SAR is typically activated in response to necrotic pathogenic bacteria and involves crucial signaling molecules that simultaneously play pivotal roles in both plant growth and defense.

## 5. Microorganisms Skills to Promote Plant Growth

As the population continues growing, commodity commercialization has been increased, while the agricultural lands have been reduced due to soil degradation. The food production sector has suffered high pressure to maintain its productivity. This particular situation requires the utilization of chemical fertilizers and pesticides. The excessive use of these chemicals may provoke problems for the environment and human diseases. Current agriculture needs alternatives that reduce cost production, environmental impact, and dependence on input reduction without reducing productivity. In this way, microbial agents, especially microorganisms, which show several abilities related to plant growth, can be used as a helpful alternative.

Microorganisms can have diverse interactions with host plants, ranging from beneficial to harmful or neutral. Microorganisms that offer multiple advantages to plants hold significant potential as biopesticides and biofertilizers, contributing to sustainable crop protection and increased agricultural output. However, the global challenge lies in encouraging farmers to adopt biofertilizers and biological control agents to reduce their reliance on chemical fertilizers and pesticides.

Notably, plant growth-promoting microorganisms have the capacity to engage with various crop plants, enhancing their support for growth and development, bolstering resistance against pathogens, and facilitating overall plant health. Many metabolites produced by these microorganisms have been identified for commercial applications due to their ability to promote plant growth, improve crop yields, enhance biocontrol efficacy, and offer suitable formulation options. Diverse biocomplexes, including biopesticides and biofertilizers, have been identified to safeguard plants against both biotic and abiotic stresses. They achieve this through the production of plant growth regulators, siderophores, improved nutrient uptake, increased yield, and the synthesis of antagonistic compounds such as hydrolytic enzymes, antibiotics, volatile compounds, and hydrogen cyanides.

### 5.1. Nitrogen Fixation for Reducing Chemical Fertilizers

Nitrogen (N) is a vital element in numerous crop production processes, with a significant impact on grain productivity. As the demand for food continues to rise, the necessity for nitrogen has also increased. Rice, maize, potatoes, and wheat are crops that benefit from enhanced nitrogen fertilizer application to boost their productivity. However, the relatively low efficiency in nitrogen utilization, attributed to factors such as ammonia volatilization, N leaching, and denitrification, is a concern. Remarkably, rice cultivation alone contributes to

21–25% of the world's total nitrogen fertilizer consumption, underscoring the crucial role of nitrogen as a macronutrient in plant physiology.

In the case of maize production, nitrogen takes center stage, as it plays a pivotal role in the synthesis of amino acids, chlorophyll, adenosine triphosphate (ATP), and nucleic acids. Consequently, increasing nitrogen fertilizer application directly correlates with maize yield potential. One potential avenue to reduce the reliance on chemical nitrogen fertilizers is biological nitrogen fixation (BNF), which accounts for over 60% of the Earth's fixed nitrogen. This emphasizes the growing importance of maximizing BNF in agriculture to meet the demands of a burgeoning global population.

To achieve this optimization, a comprehensive understanding of various nitrogen-fixing bacteria and their processes is imperative. Jia et al. identified and harnessed the potential of nitrogen-fixing bacteria, specifically Kosakonia radicincitans from Pennisetum giganteum. Their research revealed a 25% reduction in chemical fertilizer when combined with these microorganisms, resulting in increased plant height, weight, chlorophyll content, soluble protein content, soluble sugar content, vitamin C content, alkali hydrolyzed nitrogen content, and accessible phosphorus content.

Another promising avenue was explored by Song et al., who evaluated urea reduction in rice production by replacing artificial N fertilizers with cyanobacteria Anabaena azotica. Their findings indicated that substituting 50% of urea with cyanobacteria did not significantly compromise rice yield. Importantly, this approach reduced N loss considerably, especially in terms of NH4+ −N and NO3− leaching losses. By substituting A. azotica for part of the urea late in the rice season, they achieved improved soil nitrogen retention. A. azotica demonstrated its ability to intercept, fix, and delay nitrogen release, thereby enhancing the soil's nitrogen cycling dynamics and substantially reducing N leaching.

Numerous studies have been dedicated to understanding the impact of diazotroph microorganisms, such as A. azotica, on maize yield. Tapia-Garcia's work uncovered a breakthrough in identifying the most common nitrogen-fixing endophyte, Burkholderia, associated with maize. Recent studies have confirmed the significant colonization of maize tissues by these isolates, leading to increased production. Sheoran conducted comprehensive research to investigate maize–endophyte interactions and their influence on maize output, both in controlled laboratory settings and real-world field conditions. The association of Klebsiella pneumoniae with Herbaspirillum seropedicae endophytes resulted in a considerable yield increase.

Pandey et al. conducted experiments using local maize cultivars, employing Azotobacter chroococcum and Azospirillum brasilense strains. In tropical conditions, they observed a substantial 1–1.5-fold increase in maize productivity. These studies collectively underscore the promising potential of harnessing nitrogen-fixing microorganisms to enhance crop yields while reducing dependence on chemical fertilizers.

### 5.2. Phosphorus Solubilizing and Mineralizing and Siderophore Production

Phosphorus (P) stands as a critical macronutrient indispensable for plant growth and metabolism. Nonetheless, when introduced into soil, phosphorus rapidly binds to metal cations like Al, Fe, and Ca or adheres to mineral surfaces, significantly limiting its availability for plant uptake. Phosphates, integral to various physiological and biochemical processes such as photosynthesis, root and stem development, flower and seed formation, crop maturation, nitrogen fixation by legumes, and plant disease resistance, represent a pivotal factor constraining agricultural production.

Recent research has been conducted to assess the potential of eight bacterial genera, including Acinetobacter, Pseudomonas, Massilia, Bacillus, Arthrobacter, Stenotrophomonas, Ochrobactrum, and Cupriavidus, in their ability to solubilize phosphorus. The findings point to Acinetobacter as a standout candidate, showcasing a remarkable proficiency in phosphorus solubilization, thus presenting promise in the enhancement of soil fertility and quality.

Additionally, Liu et al. have demonstrated that phosphorus-solubilizing bacteria possess the capability to excrete small molecular organic acids that effectively dissolve inorganic phosphorus. This, in turn, has the potential to modify soil properties and indirectly impact the microbial community in the rhizosphere.

Another study investigated the effectiveness of bacteria such as Enterobacter cloacae, Pseudomonas pseudoalcaligenes, and Bacillus thuringiensis in the solubilization of plant-unavailable phosphorus, whether in inorganic (calcium phosphate) or organic (phytin) forms.

This research revealed that threonine plays a pivotal role in facilitating bacterial solubilization and subsequent plant uptake of various nutrients. The authors also suggested that compounds specially secreted by these bacteria could represent a promising avenue for unlocking existing phosphorus reservoirs in croplands.

In a related investigation, the ability of various genera of plant growth-promoting bacteria, including Bacillus, Enterobacter, Pseudomonas, Staphylococcus, Acinetobacter, Klebsiella, and Proteus, to solubilize substantial amounts of phosphorus from soil samples collected from the Lesser Himalayas ecosystem was explored. The results underscore the remarkable capacity of these bacteria in solubilizing phosphorus, thus implying their potential for improving soil fertility and promoting plant growth. Consequently, these bacteria may offer a means to reduce the reliance on phosphorus fertilizers.

Iron (Fe) is a crucial mineral for plant growth and development. It is typically found in two forms, Fe3+ and Fe2+. In many soils, iron exists in various forms, including insoluble hydroxides and oxyhydroxides in aerobic conditions, rendering it inaccessible for plants. However, rhizospheric bacteria play a vital role in making iron available to plants by secreting siderophores, which are low molecular weight iron-chelating compounds with a strong affinity for complexed iron. Several species of plant growth-promoting rhizobacteria (PGPR), such as Enterobacter, Pseudomonas, Azotobacter, Bacillus, Serratia, and Rhizobium, produce siderophores. These siderophores can be extracellular or intracellular, water-soluble, capable of solubilizing iron from minerals or organic molecules under iron-deficient conditions, and proficient at forming stable complexes with heavy metals and radioactive particles. The production of siderophores by these PGPR strains is advantageous for enhancing plant growth and alleviating heavy metal toxicity in contaminated soils. This ability indirectly helps plants in mitigating heavy metal stress induced by the soil.

Plants employ various mechanisms to assimilate iron from siderophores, including chelation and iron release, direct absorption of siderophore–iron complexes, and ligand exchange. Siderophores serve a dual role in iron sequestration and the mitigation of heavy metal-induced plant stress. Notably, Pseudomonads are known for generating siderophores with a high affinity for ferric ions. Research has demonstrated that siderophores produced by biocontrol pseudomonads can suppress phytopathogens like Aspergillus, Fusarium, and Pythium species. For instance, Pyoverdine, a siderophore produced by pseudomonads, has been shown to reduce Fusarium oxysporum-induced potato wilt, and it has had inhibitory effects on phytopathogens in peanuts and maize. A deficiency of iron intake can significantly limit plant growth.

In most soils, iron primarily exists in the ferric oxidation state (Fe3+), forming insoluble hydroxides with very low solubility constants, which makes it inaccessible to both plants and rhizospheric bacteria. On the other hand, the ferrous (Fe2+) state is considerably more soluble and accessible to plants. However, ferrous iron readily oxidizes to Fe3+ in the environment, leading to precipitation. To thrive in iron-deficient environments, many microorganisms have evolved high-affinity iron (Fe3+) acquisition mechanisms involving siderophores and low-molecular-mass organic molecules (iron chelators). Siderophores function as iron solubilizers by binding to Fe3+ on bacterial membranes, subsequently reducing it to Fe2%, making it available to both the microorganisms and plants in iron-deficient environments. After being released inside the cells, siderophores are excreted and recycled for iron transport.

Studies have shown that both soil salinity and iron deficiency negatively impact various aspects of plant development, including stem and root growth, photosynthesis, transpiration rates, chlorophyll concentration, and stomatal conductance. Therefore, the search for potential siderophore-producing, salt-tolerant PGPR strains could be instrumental in cultivating salt-affected regions without resorting to transgenic organisms. Notably, the plant growth-promoting bacteria Gluconacetobacter diazotrophicus and Azospirillum brasilense have been evaluated for their role in enhancing iron nutrition for strawberry plants. Hydroxamate-type siderophores were found to be more effective than catechol-type siderophores in providing iron to the plants.

Another crucial aspect to consider in the context of siderophores in the environment is their potential for abiotic degradation, which can occur through hydrolysis and/or oxidation mechanisms. For siderophores containing hydroxamate groups, hydrolysis can result in the formation of hydroxylamine moieties, which can reduce Fe3+ to Fe2+. Laboratory studies have shown that hydrolyzed products from siderophores, like coprogen, can effectively transport iron to plants, such as cucumber and maize. These findings suggest a potential siderophore utilization strategy, where the presence of "sacrificial" moieties aids in the reduction, dissolution, and delivery of iron to microorganisms. Additionally, the processes of siderophore degradation and mineral dissolution can be influenced by exposure to sunlight. The presence of chelated Fe, as well as the specific type of siderophore, can lead to distinct outcomes.

Furthermore, the study evaluated the impact of four organophosphate pesticides (acephate, glyphosate, monocrotophos, and phorate) on soil microorganisms that produce siderophores or PGPR. Various soil microorganisms, including Rhizobium leguminosarum, Pseudomonas fluorescens, Azotobacter vinelandii, Bacillus brevis, and Salmonella typhimurium, were individually and collectively tested for siderophore production in the presence of these pesticides. The results indicated a dose-dependent impact, with the pesticide mixtures having a more significant effect compared to individual pesticides. The pesticides' impact on PGPR strains varied, with Pseudomonas fluorescens being the least affected, while Salmonella typhimurium was also relatively unaffected. Overall, the study found that the pesticides had adverse effects on the various PGPR strains, with varying degrees of impact.

In summary, iron is a vital element for plant growth, and siderophores produced by rhizospheric bacteria play a critical role in making iron available to plants, especially in iron-deficient environments. These siderophores have additional benefits in mitigating heavy metal stress and suppressing phytopathogens. Furthermore, the interaction between siderophores, iron, and various environmental factors is complex and can have far-reaching implications for plant health and soil ecosystems.

## 6. Future Perspectives

Plant growth-promoting rhizobacteria (PGPR) represent a valuable group of soil bacteria known for their ability to inhabit plant roots and promote plant growth and health through a variety of mechanisms. These beneficial microorganisms enhance plant growth by improving nutrient availability, synthesizing plant growth hormones, encouraging root development, and safeguarding plants from diseases and pests. The future of PGPR holds great promise, particularly in the realms of agriculture and horticulture, as they offer a means to enhance plant growth while reducing the reliance on synthetic fertilizers and pesticides, and concurrently improving soil quality.

Anticipated directions for future PGPR research include the development of more effective bacterial strains for promoting plant growth and a deeper understanding of the molecular mechanisms underlying the interactions between PGPR and plants. This research could lead to the advancement of agricultural practices that minimize the use of chemical inputs, offering more efficient and sustainable alternatives.

The application of PGPR in biofertilizers and biopesticides is also expected to grow. Biofertilizers containing PGPR can enrich soil fertility and enhance plant growth and yield by providing essential nutrients. Likewise, biopesticides with PGPR can contribute to ecologically friendly approaches for managing plant diseases and pests.

Furthermore, the integration of PGPR into crop breeding and genetic engineering efforts has the potential to yield cultivars that are more resilient against environmental stressors, including drought, salinity, and plant diseases. This could result in the development of more durable and sustainable crop varieties capable of withstanding changing environmental conditions, thus contributing to food security.

In summary, PGPR represent a sustainable and environmentally friendly alternative to traditional agricultural practices. They hold the promise of fostering more sustainable and resilient agriculture while promoting the reduction of synthetic chemical inputs.

## 7. Conclusions

This review underscores the promise of biologically reliant tools, particularly Plant Growth-Promoting Rhizobacteria (PGPR), in mitigating global food production challenges. However, before these instruments can be effectively utilized in practical scenarios, it's clear that there exist substantial knowledge gaps that need to be addressed. PGPR may hold the solution to sustainable crop yields and improved nutrient management.

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