



REVIEW ARTICLE

Role of plant growth promoting rhizobacteria in sustainable agriculture

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Abstract

One of the significant challenges facing the world today is the growing population, which currently stands at approximately 8.2 billion and is projected to reach approximately 9.7 billion in the next 25–26 years. By 2050, food production must increase fourfold to satisfy global food demand. We must transition to more sustainable agricultural practices. These practices should prioritize the development of sustainable methods that enable crops to thrive in resource-limited environments and under various environmental stressors. Additionally, the focus should be on creating crops that utilize resources more efficiently and achieve optimal sustainable yields across a broader range of conditions, thereby highlighting plant growth-promoting rhizobacteria (PGPR) importance for long-term agricultural sustainability.

Keywords

PGPR; plant nutrition; rhizosphere; sustainable agriculture

Introduction

Food is essential for the growth and development of all living beings and increasing demand for food has led to the use of deceptive methods to increase food production. Frequent application of chemical inputs such as insecticides, herbicides and chemical fertilizers. Pesticide runoff from such lands negatively affects life on Earth through bioaccumulation and biomagnification (1). They endanger human and animal health, pollute food chains, disturb ecosystems and decrease biodiversity. They can also deteriorate soil health and produce pests that are resistant over time.

One eco-friendly approach to increase food production is to use PGPR. These include the solubilization of phosphate, the biological fixation of atmospheric nitrogen and the synthesis of phytohormones like cytokinins, gibberellins and indole-3-acetic acid (IAA), which all work together to promote plant growth and development. Additionally, PGPR produces antimicrobial chemicals that reduce phytopathogens and induce systemic resistance, which minimizes the occurrence of disease.

Microorganisms found in the rhizosphere are important biological resources that help plants tolerate high levels of metal toxicity while also improving the overall effectiveness of phytoremediation. These microorganisms provide disease prevention, soil structure preservation and nutrient recycling. Additionally, they are essential in lowering the toxicity and bioavailability of metals in the soil, which supports sustainable soil management and healthier plant growth.

Addressing the world's future economic demands requires an understanding of the importance of sustainable farming, which can improve soil quality and plant health while reducing the need for artificial fertilizers and pesticides (2). PGPR increases plant vitality and fosters development without emitting toxic byproducts into the atmosphere (3). The type genus for the Streptomycetaceae family of PGPRs, the largest genus in the phylum Actinobacteria, is *Streptomyces*, with over 500 species (4).

The metabolic activities of rhizosphere bacteria are essential for carbon cycling and halting soil carbon loss. The most potent biological agents against bacterial and fungal plant diseases are PGPR. By helping plants become more resilient to biotic and abiotic stressors, these advantageous microorganisms, which are an essential part of the phyto-microbiome, improve overall agricultural production. By creating chemical signals, improving nutrient absorption and manufacturing antibiotics (5).

Role of rhizobial interactions in promoting plant growth

Beneficial microbes, known as rhizosphere microorganisms, employ various techniques to encourage plant growth. Numerous biotic and abiotic elements affect the rhizosphere ecology in both natural and farmed soils and these elements can modify the effects of PGPR on plant health. According to their functional role, PGPRs are classified

as biofertilizers, which make nutrients more accessible to plants (6). Biopesticides control diseases primarily by producing antibiotics and antifungal metabolites, rhizo-remediators that decompose organic pollutants and phyto-stimulators, which mainly utilize phytohormones to stimulate plant growth (7). Furthermore, a single PGPR usually exhibits multiple mechanisms of action, including biological regulation, in many of the cases studied (8,9). According to the studies, role of some rhizobacteria with action mechanism is given in Table 1 (1). PGPRs promote plant growth through both direct and indirect mechanisms (Fig. 1). Direct mechanisms include nitrogen fixation, phytohormone production, phosphate solubilization, siderophore production etc., while indirect mechanism includes antibiotic production, protection against pathogens by developing resistance, increases stress tolerance, etc.

Table 1. Function and action mechanism of the rhizosphere by a few chosen PGPR with specific plants

Species	Role	Mechanism involved	Plant	Reference
<i>Agrobacterium radiobacter</i>	Improves bioprotection	Antibiotics		(10)
<i>Azotobacter chroococcum</i>	Assists in biostimulation	Production of gibberellin	Cereals	(11)
<i>Azospirillum brasilense</i>	Biofertilisation	Phosphate solubilisation	Maize (<i>Zea mays</i>), Wheat (<i>Triticum aestivum</i> L.) and Rice (<i>Oryza sativa</i>)	(12)
<i>Bacillus cereus</i>	Biofertilisation	Lipopeptides Induced and acquired systemic resistance	Bean (<i>Phaseolus vulgaris</i>) Tomato (<i>S. lycopersicum</i>)	(13)
<i>Bacillus subtilis</i>	Biofertilisation Aids in biostimulation Bioprotection	Ammonia synthesis Through IAA and Cytokinin production Lipopeptides Catalase production	Maize (<i>Zea mays</i>) Chickpea (<i>Cicer arietinum</i>) Tomato (<i>S. lycopersicum</i> L.) Cucumber (<i>Cucumis sativus</i>)	(14) (15)
<i>Klebsiella pneumonia</i>	Aids biofertilisation Bioprotection	Nitrogen fixation Acquired and induced systemic resistance	Maize (<i>Zea mays</i>) Peanut (<i>Arachis hypogaea</i>)	(16)
<i>Pseudomonas aeruginosa</i>	Bioremediation	Cellulase production	Rice (<i>O. sativa</i>), Pea (<i>P. sativa</i>)	(17)
<i>Staphylococcus saprophyticus</i>	Biostimulation	Manufacturing of IAA	Ornamental species	(18)

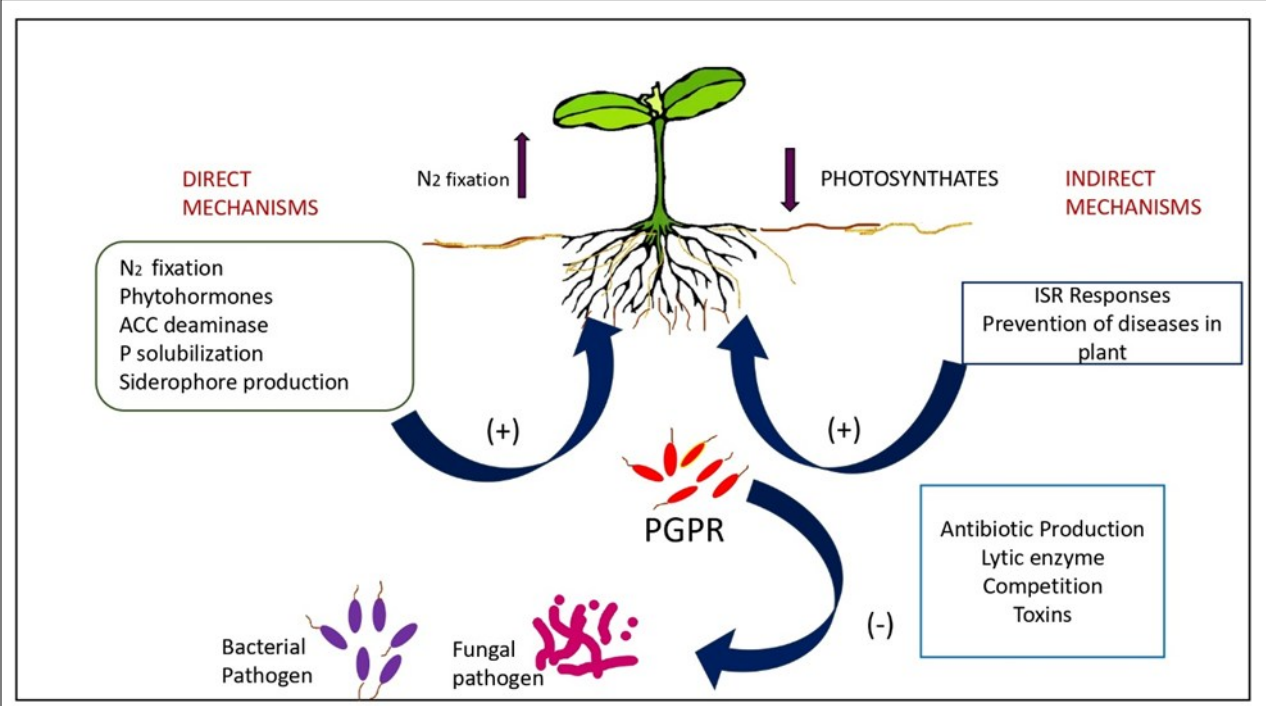


Fig. 1. Benefits of plant growth promoting rhizobacteria in plants.

Nitrogen fixation

Nitrogen is the most important nutrient for plant growth and productivity is nitrogen (N). Although nitrogen accounts for approximately 78 % of the atmosphere, it is unavailable for plants to use.

Nitrogen fertilizers are a necessary component of crop growth techniques in modern agriculture. However, their excessive and ongoing use results in environmental pollution, eutrophication, lethal environmental discharges and toxic deposits in groundwater and other water bodies, all of which directly or indirectly contribute to climate change (19). Biological Nitrogen Fixation (BNF) converts atmospheric nitrogen (N_2) into forms that can be used by plants. Using a complex enzyme system known as nitrogenase, nitrogen-fixing microorganisms transform nitrogen into ammonia (20).

Unlike free-living nitrogen-fixers and their host plants, symbiotic nitrogen-fixing organisms establish mutually advantageous relationships with their hosts. The nitrogen fixers that work in harmony include *Rhizobium*, *Azoarcus*, *Mesorhizobium*, *Frankia*, *Burkholderia* and several other strains of *Achromobacter*. Legumes fix nitrogen from the atmosphere through symbiotic connections with bacteria, which lowers their requirement for extra nitrogen until significant amounts of N fertilizers are introduced. They reduce or cease nitrogen fixation because the supplied fertilizer requires less energy than atmospheric N_2 repair. The field is sprayed with biological N_2 -fixing PGPR, which increases growth, fights illness and keeps the soil nitrogen stable. PGPR can also enhance plant growth by triggering Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR) in plants is a defense system that plants employ to fend off harmful bacteria, fungi and viruses.

Phosphorus solubilization, mineralization and siderophore production

Eight bacterial genera, *Acinetobacter*, *Pseudomonas*, *Massilia*, *Bacillus*, *Arthrobacter*, *Stenotrophomonas*, *Ochrobactrum* and *Cupriavidus*, have the potential to solubilize phosphorus (21). The findings revealed that *Acinetobacter* demonstrated a significant capacity for phosphorus solubilization, positioning it as a promising application for improving soil quality and fertility. Additionally, inorganic phosphorus can be dissolved by tiny organic acids that bacteria can expel, thereby potentially impacting soil properties and indirectly influencing the microbial community in the rhizosphere (22).

Another crucial mineral for plants is iron (Fe). They are typically found in the form of Fe^{3+} and Fe^{2+} . In soil, iron can exist in various states, like oxyhydroxides and insoluble hydroxides, under aerobic conditions, rendering it inaccessible for plant uptake. Siderophores are secreted by rhizospheric bacteria and are small iron chelators that strongly favour complex iron. Various PGPR such as *Enterobacter*, *Pseudomonas*, *Azotobacter*, *Bacillus*, *Serratia* and *Rhizobium* produce siderophores that can exist either inside or outside the cell. They are water-soluble, can mobilize iron from organic to mineral compounds when iron is scarce and have the potential to combine with radioactive particles and heavy metals to form stable complexes. Plants take up iron from siderophores using different methods, such as chelating and releasing iron, directly absorbing siderophore-iron complexes and exchanging ligands. Siderophores serve the dual purpose of sequestering iron and alleviating the plant stress caused by heavy metals. In iron-deficient environments, siderophores act as iron solubilizers by binding Fe^{3+} to bacterial membranes and subsequently reducing it to Fe^{2+} , which makes it available to both them and plants. After being freed inside

the cells, siderophores are expelled and recycled for iron transportation (23).

Production of phytohormones

PGPR creates phytohormones and modifies the hormonal equilibrium of plants. Plant hormones control factors such as mineral nutrition, water relations and disease resistance. Auxin, cytokinin and gibberellins are among the several phytohormones produced by PGPR. These substances, which are needed in small amounts, are produced in different areas of the plants and move along a concentration gradient from regions of higher concentration to those of lower concentration within the plant (24,25). In plants, phytohormones are essential for several physiological functions, including stomatal movement, growth, differentiation, development, flowering and fruit ripening. The ability of PGPRs to generate or alter phytohormone levels is one of the main ways they stimulate plant development (24,26).

Abiotic stress tolerance

The primary cause of decline in agricultural productivity is thought to be abiotic stressors. However, plant factors (physiological anomalies such as sensitivity to illnesses and abscission) and soil type (absence of dietary and hormonal abnormalities) affect the degree of abiotic stress (27). *Bacillus lentimorbus* enhanced the growth and antioxidant potential of consumable portions of lettuce, spinach and carrots. These effects are significant, particularly in terms of improving the nutritional value of these crops (28). *Azospirillum* has also been used to investigate the growth of lettuce under saline stress. Inoculation of lettuce with *Azospirillum* sp. not only increased the yield but also prolonged the storage lifespan of lettuce cultivated under salt stress (29).

Antibiotic biosynthesis

When it comes to managing plant diseases in crops, microbial antagonists offer a natural substitute for traditional pesticides. By producing antibiotics, *Bacillus* sp., *Pseudomonas* sp. and PGPR help in inhibiting the growth of harmful bacteria. The production of antibiotics by PGPR to fight different plant diseases has been one of the most promising developments in plant sciences over the last 20 years and it is a biocontrol mechanism that has been extensively researched (30). Numerous lipopeptide antibiotics, including bacillomycin and surfactin, as well as a wide range of additional antibacterial and antifungal substances, are produced by *Bacillus* sp. There are two types of bactericides: volatile and non-volatile. Polyketides, cyclic lipopeptides, amino polyols and heterocyclic nitrogenous substances are a few types of non-volatile antibiotics. On the other hand, volatile antibiotics include compounds like hydrogen cyanide, alcohols, aldehydes and ketones, among others (31).

Role of nanotechnology in agriculture

Nanotechnology is the study and application of materials with sizes mostly less than 100 nm. Nanomaterials in this size range exhibit distinct optical and chemical characteristics (32). Nanotechnology has produced a variety of agricultural instruments, including nano sensors, nano pesticides and nano fertilizers. The effectiveness of nano fertilizers is much higher compared to normal conventional fertilizers as they minimize loss of nitrogen, which is caused due to emission, leeching and long-term assimilation by soil microorganisms (33,34). Crop yield is severely hampered by diseases and precisely determining the best time to prevent these diseases is a difficult task in disease management.

Viral infections are the most difficult to control among diseases because vectors must be targeted to stop their transmission. Therefore, accurately identifying stages, such as viral DNA replication or the initial production of viral proteins, is crucial for successfully controlling diseases, especially viral infections. To precisely identify the virus strain and identify the best time for therapeutic intervention to stop disease progression, nano-based viral diagnostics, including the creation of multiplexed diagnostic kits, have accelerated. These diagnostic kits based on nanotechnology not only boost the detection speed but also the detection power (35).

PGPR as biofertilizer

Biofertilizers include living microorganisms that expand the supply of nutrients for plants. They are eco-friendly and renewable substitutes for chemical fertilizers. To increase the number of these good microbes that are mutualistic and accelerate microbial processes, which increases the availability of nutrients that can then be readily assimilated and absorbed by the plants, biofertilizer is a mixture of live or latent cells that encourage nitrogen fixation and cellulolytic and phosphate-solubilizing microorganisms (36). A suitable rhizosphere for plant growth and the conversion of nutritionally significant components through biological processes, such as boosting the availability of N, P and K and inhibiting the growth of pathogens, are facilitated by adequate PGPR densities in biofertilizers (37,38). PGPR can be categorized as a biofertilizer if it serves as a source of plant nutrition and enrichment that replenishes or restores the nutritional cycle between the soil, plant roots and existing microbes. Conventional methods of using PGPR as fertilizer are ineffective because 90 % of them are lost to the air after application, they are not tolerant of the environment (UV, heat, etc.) and they affect farmer's application expenditure by runoff.

Problems, challenges and opportunities

The need to feed a world population that is expanding and becoming more urbanized has made scientists aware that they must address this crucial issue in their studies. By 2050, it is predicted that 10 billion people will live globally, with a higher concentration in developing nations. Although increased agricultural production is required, these methods involve widespread use of non-renewable natural resources, including water, agricultural soil, rock phosphate reserves, fossil fuels and other energy sources. Furthermore, environmental pollution comes from energy-intensive industrial processes used to produce fertilizers, as well as runoff or leaching of soluble nutrients from agrochemicals used in aquatic systems (39). Global agricultural techniques are currently being adopted and many strategies are being considered to achieve sustainable economic and environmental advances, with the ultimate goal of sustaining output while protecting the biosphere. "Sustainable development" is the outcome of the interactions between three main factors-the environment, society and economy-as well as the intersections between them. Thus, the concept of "sustainable development" is ultimately determined by the confluence of the economy-environment (agro-ecology), environment-society (environmental awareness) and society-economy (living standard) (40-42).

Future prospects of PGPR

In the framework of environmentally conscious and sustainable agriculture, high crop yields, increased productivity and enhanced soil fertility are essential. Research must therefore concentrate on

the new idea of rhizo-engineering, which relies on the deliberate application of special biomolecules that foster interactions between microbes and plants. The development of biotechnological and molecular strategies that can enhance our comprehension of microbial dynamics and promote integrated soil microbial management is what will shape rhizosphere biology in the future. Although a lot of studies have been done on how PGPR solubilize nitrogen and phosphate, comparatively little is known about how they solubilize potassium, the third main necessary macronutrient. In addition to broadening the range of microbial inoculants, expanding this field of research may boost farmers' confidence in implementing these technologies. In order to promote broad acceptance among farmers, future research should focus on optimizing the PGPR formulation, including shelf life, environmental tolerance and crop safety, while maintaining cost-effectiveness (24).

Conclusion

With an emphasis on PGPR and their effects on plant growth, this study offers a thorough review of the microbial colonization of roots. This study discusses the processes that lead to root colonization, including adhesion, chemotaxis, biofilm development and signalling molecules, all of which promote mutually beneficial interactions. Utilizing the relationship between crops and soil microbes is a pertinent strategy for boosting food production for the world's expanding population at the lowest possible environmental cost in the current climate of global change. Approximately one billion people were spared starvation and undernourishment seven decades ago, when the Green Revolution boosted agricultural production worldwide and led to the invention of artificial fertilizers, among other innovations. Humans have participated in a range of activities since the beginning of humanity, which have had an impact on our ecology, either positively or negatively. The conventional crop strategy must end the overuse of the soil ecosystem because anthropogenic activities, including monocultures of crops, intensive farming and the application of agrochemicals, are serious issues that disrupt the ecosystem. The application of PGPR will definitely come to pass and will play a key role in important processes that safeguard the production and stability of agroecosystems, guiding us toward an ideal agricultural system. This finding emphasizes that PGPR is a promising alternative to chemical inputs, potentially leading to higher yields. However, further field research is required to fully explore its potential and develop its practical applications.

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Authors' contributions

All authors made substantial contributions to conception and design, acquisition of data or analysis and interpretation of data.

Compliance with ethical standards

Conflict of interest: Authors have no conflicts of interest to declare.

Ethical issues: None

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