

Green Chemistry in the Soil: Harnessing Plant Growth-Promoting Rhizobacteria for Sustainable Agriculture

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ABSTRACT

Agricultural productivity has increased considerably with the widespread use of chemical fertilizers and pesticides. However, excessive dependence on these agrochemicals has led to several environmental problems, including soil degradation, water contamination, and risks to human health. In this context, sustainable agricultural approaches that utilize beneficial microorganisms have gained significant attention. Plant Growth-Promoting Rhizobacteria (PGPR) are a group of soil bacteria that colonize the rhizosphere and enhance plant growth through a variety of biological mechanisms. These microorganisms promote plant development directly by fixing atmospheric nitrogen, solubilizing phosphate, producing phytohormones, and releasing extracellular enzymes that improve nutrient availability. In addition, PGPR indirectly support plant health through biocontrol activities such as antibiotic production, siderophore secretion, and the induction of systemic resistance against pathogens. The application of PGPR in agriculture includes seed treatment, soil inoculation, foliar application, and biofertilizer formulations. Despite their promising potential, several limitations such as field variability, competition with native microorganisms, and survival of microbial inoculants affect their large-scale use. Continued research focusing on microbial consortia development, molecular characterization, and improved formulation technologies may further enhance the effectiveness of PGPR in sustainable crop production.

Keyword: - Plant Growth-Promoting Rhizobacteria (PGPR); Sustainable Agriculture; Biofertilizers; Nitrogen Fixation; Phosphate Solubilization; Rhizosphere Microbiology; Biocontrol Agents.

1. INTRODUCTION

Modern agriculture has significantly increased crop yields through chemical fertilizers and pesticides. However, excessive agrochemical application has resulted in soil degradation, environmental pollution, and health risks (Kouassi, 2001; Thakore, 2006). Biofertilizers and biological control agents have been proposed as sustainable alternatives (De Leij et al., 2001; Leila & El-Hafid, 2020). PGPR in Agriculture Chemistry). Plant Growth-Promoting Bacteria (PGPR), also termed plant growth-promoting rhizobacteria (PGPR), are beneficial soil microorganisms that enhance plant growth directly or indirectly through various biochemical processes (Glick, 2004; Vessey, 2003). Green chemistry in agriculture focuses on reducing harmful chemical inputs while maintaining soil fertility and crop productivity. One of the most promising approaches is the use of Plant Growth-Promoting Bacteria (PGPR)—beneficial soil microorganisms that naturally improve plant growth and soil health. PGPR lives in the rhizosphere (the region around plant roots) and supports plants through various biochemical processes. They fix atmospheric nitrogen into a usable form, solubilize insoluble phosphates, and produce organic acids and enzymes that enhance nutrient availability. Some species also synthesize plant hormones like indole-3-acetic acid (IAA), which promotes root development and overall plant growth. Beyond nutrition, PGPR acts as a natural protector. They produce antibiotics, siderophores (iron-chelating compounds), and enzymes that suppress harmful pathogens. Additionally, they stimulate the plant's own defense system through induced systemic resistance (ISR), making crops more resilient to diseases and environmental stress. By reducing the need for synthetic fertilizers and pesticides, PGPR contributes to cleaner soil, lower environmental pollution, and sustainable agricultural practices. In this way, they represent a living example of green chemistry—where biological processes replace harmful chemicals to create a safer and more sustainable farming system.

2. PLANT GROWTH-PROMOTING BACTERIA: DIVERSITY AND CLASSIFICATION

Plant Growth-Promoting Bacteria (PGPR) are a diverse group of beneficial microorganisms that enhance plant growth and soil fertility. They are commonly found in the **rhizosphere** (soil surrounding plant roots), on root

surfaces, or sometimes inside plant tissues (endophytes). These bacteria establish symbiotic or associative relationships with plants and play a vital role in sustainable agriculture. PGPR belongs to several bacterial genera, including *Azotobacter*, *Azospirillum*, *Rhizobium*, *Bacillus*, *Pseudomonas*, *Enterobacter*, and *Serratia*. Based on their interaction with plants, they are broadly classified into:

- 1.1. **Symbiotic Bacteria** – These form close associations with plant roots, such as *Rhizobium*, which forms nodules in legumes and fixes atmospheric nitrogen.
- 1.2. **Free-Living Bacteria** – These exist independently in the soil and promote plant growth without forming nodules, such as *Azotobacter* and *Bacillus*.
- 1.3. **Endophytic Bacteria** – These live inside plant tissues without causing harm and contribute to nutrient uptake and stress tolerance. Functionally, PGPR are also classified based on their mechanisms of action:
 - 1.4. **Direct promoters** (e.g., nitrogen fixation, phosphate solubilization, hormone production)
 - 1.5. **Indirect promoters** (e.g., pathogen suppression, induced systemic resistance)This diversity makes PGPR highly adaptable and effective across different crops and environmental conditions, highlighting their importance in modern sustainable farming systems. (Compant et al., 2005; Yadav et al., 2017).

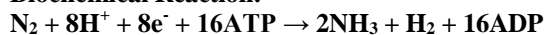
3. DIRECT MECHANISMS OF PLANT GROWTH PROMOTION

Direct mechanisms of plant growth promotion refer to the ways in which Plant Growth-Promoting Bacteria (PGPR) enhance plant development by directly improving nutrient availability and regulating plant physiology. These mechanisms primarily support plant nutrition and growth at the biochemical level. One of the most important direct mechanisms is biological nitrogen fixation, where certain bacteria convert atmospheric nitrogen (N₂) into ammonia (NH₃), a form that plants can absorb and use for protein synthesis. This reduces the need for chemical nitrogen fertilizers. Another key mechanism is phosphate solubilization. Many soils contain phosphorus in insoluble forms that plants cannot utilize. PGPR releases organic acids and enzymes that convert insoluble phosphates into soluble forms, thereby increasing phosphorus availability for root uptake. PGPR also produce phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins. These hormones stimulate root elongation, increase root surface area, and improve nutrient absorption. Some bacteria produce ACC deaminase, an enzyme that lowers plant stress by reducing excess ethylene levels. Additionally, PGPR secrete enzymes that enhance the breakdown of organic matter, contributing to improved soil fertility and nutrient cycling. Through these direct biochemical activities, PGPR promotes healthier plant growth, better nutrient uptake, and higher crop productivity in a sustainable manner.

3.1 Nitrogen Fixation

Nitrogen is essential for protein synthesis and plant growth. Atmospheric nitrogen (N₂) is unavailable to plants and must be biologically fixed into ammonia (NH₃) by nitrogenase enzymes (Puig & Normand, 2009). Symbiotic bacteria (*Rhizobium*) and free-living bacteria (*Azotobacter*, *Azospirillum*) contribute significantly to nitrogen fixation (Dobbelaere et al., 1997; Vessey, 2003).

Biochemical Reaction:



Nitrogen fixation reduces synthetic fertilizer usage and nitrate contamination (Howarth, 2010).

3.2 Phosphate Solubilization

Phosphorus is often present in insoluble forms such as tricalcium phosphate. PGPR solubilize phosphorus by: Secretion of organic acids (gluconic acid, citric acid), Proton extrusion, Production of phosphatase and phytase enzymes. Genera involved include *Bacillus*, *Pseudomonas*, and *Rhizobium* (Rodriguez & Fraga, 1999; Gulati et al., 2004). Lowering soil pH enhances phosphorus bioavailability and root development (Glick, 2012).

3.3 Enzymatic Activities

Plant Growth-Promoting Bacteria (PGPR) produce various extracellular enzymes that help break down complex organic materials present in the soil. These enzymes are released outside the bacterial cell and play an important role in nutrient cycling, making nutrients available to plants.

For example, cellulase breaks down cellulose from plant residues into simpler sugars, helping in carbon recycling. Protease decomposes proteins into amino acids, contributing to nitrogen availability in the soil. Amylase converts starch into simple sugars, while urease breaks down urea into ammonia, which plants can absorb as a nitrogen source. By decomposing organic matter, these enzymes improve soil fertility, enhance nutrient availability, and maintain soil health. Thus, extracellular enzyme production by PGPR is an essential mechanism supporting sustainable agriculture. PGPR produce extracellular enzymes that facilitate nutrient cycling:

| Enzyme | Function | Role in Agricultural Chemistry |
|-----------|--------------------------|--------------------------------|
| Cellulase | Degrades cellulose | Carbon cycling |
| Amylase | Hydrolyzes starch | Organic matter decomposition |
| Protease | Degrades proteins | Nitrogen mineralization |
| Urease | Converts urea to ammonia | Nitrogen transformation |

Enzymatic degradation of organic matter enhances soil fertility (Kour et al., 2019).

3.4 Phytohormone Production

Plant Growth-Promoting Bacteria (PGPR) enhance plant development not only by improving nutrient availability but also by synthesizing important plant growth regulators (phytohormones). These hormones directly influence plant growth, root development, and stress tolerance.

3.4.1. Indole-3-acetic acid (IAA): IAA is a type of auxin produced by many PGPR. It stimulates root elongation, increases root branching, and enhances root hair formation. A well-developed root system improves water and nutrient absorption, leading to better plant growth.

3.4.2. Gibberellins: Gibberellins promote stem elongation, seed germination, flowering, and fruit development. Bacterial production of gibberellins helps plants grow taller and improves overall crop yield.

3.4.3. Cytokinins: Cytokinins stimulate cell division and delay leaf aging (senescence). They promote shoot growth and help maintain chlorophyll content, resulting in healthier and greener plants.

3.4.4. ACC Deaminase: Some PGPR produce the enzyme ACC deaminase, which lowers plant ethylene levels. Ethylene is a stress hormone that increases under drought, salinity, or pathogen attack. By reducing excess ethylene, ACC deaminase helps plants tolerate environmental stress and maintain normal growth.

Through the production of these growth regulators, PGPR plays a crucial role in enhancing plant development and improving crop productivity in sustainable agriculture. These hormones improve root architecture and plant vigor (Glick, 2004) **INDIRECT MECHANISMS:**

4. BIOCONTROL ACTIVITY

Plant Growth-Promoting Rhizobacteria (PGPR) play an important role in protecting plants from harmful pathogens through biocontrol activity. Instead of using chemical pesticides, PGPR naturally suppresses disease-causing microorganisms in the soil, making agriculture safer and more sustainable. One major mechanism is antibiotic production. Certain PGPR produce antimicrobial substances that inhibit the growth of fungi and bacteria responsible for plant diseases. (Haas & Défago, 2005). Another important mechanism is siderophore production. Siderophores are compounds that bind iron tightly. By capturing iron from the soil, PGPR limits its availability to pathogens, thereby restricting their growth while supplying iron to plants. (Schwyn & Neilands, 1987; Raaijmakers et al., 2002). PGPR also produces lytic enzymes such as chitinase, cellulase, and protease, which break down the cell walls of fungal pathogens and reduce infections. (Ordentlich et al., 1988). In addition, PGPR competes with pathogens for space and nutrients around the root surface. Rapid colonization of the rhizosphere prevents harmful microbes from establishing themselves. (Elad & Stewart, 2007). Some PGPR stimulate the plant's natural defense system through Induced Systemic Resistance (ISR). This strengthens the plant's internal defense mechanisms, making it more resistant to future infections. (Van Loon et al., 1998; Pieterse et al., 2002). Through these combined actions, PGPR serves as natural biocontrol agents, reducing the need for chemical pesticides and supporting sustainable agricultural practices.

5. ROLE OF PGPR IN AGRICULTURAL CHEMISTRY

Plant Growth-Promoting Bacteria (PGPR) play a significant role in agricultural chemistry by influencing soil chemical properties, nutrient transformations, and overall soil fertility. They act as natural biofertilizers and biocontrol agents, reducing the dependency on synthetic agrochemicals. One of the major roles of PGPR is in **nutrient cycling**. They convert atmospheric nitrogen into ammonia through biological nitrogen fixation, solubilize insoluble phosphates using organic acids, and mobilize essential nutrients such as potassium and micronutrients. These biochemical reactions enhance nutrient availability in the soil. PGPR also modifies **soil chemistry** by altering soil pH, producing chelating agents like siderophores, and improving cation exchange capacity. These changes increase the solubility and uptake of essential nutrients by plants. Through the production of extracellular enzymes, PGPR accelerates the **decomposition of organic matter**, leading to improved soil structure and fertility. Additionally, they help reduce heavy metal toxicity by transforming metals

into less harmful forms. By decreasing the need for chemical fertilizers and pesticides, PGPR contributes to environmentally friendly farming practices. Thus, in agricultural chemistry, PGPR serve as biological catalysts that enhance soil health, nutrient efficiency, and sustainable crop production.

2. AGRICULTURAL APPLICATIONS OF PLANT GROWTH-PROMOTING BACTERIA (PGPR)

Plant Growth-Promoting Bacteria (PGPR) are widely used in agriculture to enhance crop productivity and soil health. Their application methods are designed to ensure effective colonization of plant roots and maximum biological activity. The major agricultural application methods are described below:

6.1 Seed Treatment

Seed treatment is one of the most common and economical methods of applying PGPR. In this method, seeds are coated with a bacterial suspension or biofertilizer formulation before sowing. Seeds are mixed with a carrier-based or liquid PGPR culture. An adhesive (such as gum Arabic or jaggery solution) may be used to ensure proper coating. Treated seeds are shade-dried and sown immediately. Advantages are It Ensures early root colonization, improves seed germination and seedling vigor, enhances root development and nutrient uptake, Protects seedlings from soil-borne pathogens. Seed treatment is widely used for crops such as legumes, cereals, and vegetables, especially when applying *Rhizobium*, *Azotobacter*, or *Azospirillum* cultures.

6.2 Soil Inoculation

In soil inoculation, PGPR is directly introduced into the soil to enhance microbial population around plant roots. There are three methods of Soil Inoculation, Mixing biofertilizer with compost or farmyard manure (FYM) and broadcasting in the field and Application through irrigation systems and Direct soil drenching near the root zone. It Improves overall soil microbial activity. It enhances nutrient solubilization and mineralization. It is Suitable for large-scale field crops. Soil inoculation is particularly effective in nutrient-deficient soils and helps in improving soil fertility over time.

6.3 Foliar Spray

In this method, liquid formulations of PGPR are sprayed directly onto plant leaves. The purpose of Foliar Spray is for Rapid delivery of beneficial microbes, Induction of systemic resistance (ISR) and for Enhanced stress tolerance under drought or salinity conditions. Foliar Spray Improves chlorophyll content, enhances plant immunity and promotes better flowering and fruiting. Foliar application is commonly used during specific growth stages to boost plant performance.

6.4 Biofertilizer Formulations

PGPR are commercially available as biofertilizers in various formulations such as Carrier-based formulations (peat, lignite, vermiculite), Liquid formulations and Granular formulations. The Characteristics of good biofertilizers are High viable cell count, long shelf life, Compatibility with crops and soil conditions and Easy storage and transportation. Biofertilizers provide a sustainable alternative to chemical fertilizers and are often integrated into Integrated Nutrient Management (INM) systems. The agricultural application of PGPR through seed treatment, soil inoculation, foliar spray, and biofertilizer formulations ensures effective plant-microbe interaction. These methods enhance nutrient availability, promote plant growth, suppress pathogens, and reduce dependency on chemical inputs. Proper application techniques are essential to achieve maximum benefits and ensure sustainable agricultural productivity. Environmental factors such as soil pH, temperature, moisture, and organic carbon influence effectiveness (Nannipieri et al., 2003).

7. CHALLENGES AND FUTURE PROSPECTS

Plant Growth-Promoting Bacteria (PGPR) have great potential in sustainable agriculture, but their successful large-scale application faces several practical challenges.

7.1 Challenges

Field Variability: The performance of PGPR often varies under different field conditions. Factors such as soil type, temperature, pH, moisture, crop species, and farming practices can influence bacterial activity. A strain that performs well in laboratory or greenhouse conditions may not show the same efficiency in open-field environments. **Competition with Native Microflora:** Introduced PGPR must compete with naturally occurring soil microorganisms for nutrients and root colonization sites. Native microflora may suppress or outcompete the applied strains, reducing their effectiveness. **Inoculant Survival:** Maintaining high viability of bacterial inoculants during storage, transportation, and after application is challenging. Environmental stresses such as UV radiation, desiccation, and extreme temperatures can reduce bacterial survival and activity in the soil.

7.2 Future Prospects

Despite these challenges, the future of PGPR in agriculture is promising. Research and technological

advancements can improve their reliability and effectiveness. Microbial Consortia Development: Instead of using single bacterial strains, combining multiple compatible strains (consortia) can enhance nutrient solubilization, stress tolerance, and disease resistance. Consortia can provide synergistic effects and better adaptability under field conditions. Molecular Characterization: Advances in molecular biology and genomics allow detailed study of genes responsible for nitrogen fixation, phosphate solubilization, hormone production, and stress tolerance. Genetic characterization helps in selecting efficient strains and improving their performance. Precision Agriculture Integration: Integration of PGPR with precision farming technologies—such as soil sensors, GPS-based application systems, and data-driven nutrient management—can ensure targeted and efficient use of biofertilizers. Commercial Scale Production: Improvement in formulation technology, carrier materials, and shelf-life stability is essential for large-scale commercialization. Developing cost-effective and stable biofertilizer products will encourage farmer adoption.

8. CONCLUSIONS

Plant Growth-Promoting Rhizobacteria represent an important biological resource for improving agricultural sustainability. These beneficial microorganisms enhance plant growth through multiple mechanisms, including nitrogen fixation, phosphate solubilization, production of plant growth regulators, and enzymatic breakdown of organic matter. In addition to improving nutrient availability, PGPR also act as natural biocontrol agents by suppressing plant pathogens through antibiotic production, siderophore activity, and the stimulation of plant defense responses. The integration of PGPR into agricultural practices can significantly reduce the dependence on chemical fertilizers and pesticides while improving soil fertility and crop productivity. Their application through seed treatment, soil inoculation, foliar sprays, and biofertilizer formulations has shown considerable promise in various cropping systems. However, challenges such as environmental variability, microbial competition, and inoculant survival must still be addressed for consistent field performance. Future advancements in biotechnology, formulation science, and precision agriculture are expected to improve the efficiency and commercial viability of PGPR-based products. With continued research and proper management practices, PGPR have the potential to become a key component of environmentally friendly and sustainable agricultural systems.

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