

Harnessing Plant Growth-Promoting Microorganisms (PGPM) as Biofertilizers: A Pathway to Sustainable Crop Productivity and Soil Health

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.56557/pcbmb/2025/v26i3-49209>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://prh.ikpress.org/review-history/12937>

Review Article

Received: 24/01/2025

Accepted: 27/03/2025

Published: 29/03/2025

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ABSTRACT

Plants face numerous biological and environmental challenges, exacerbated by climate change. Chemical solutions like fertilizers and pesticides raise concerns, making eco-friendly alternatives like plant growth-promoting microorganisms (PGPM) essential. PGPM enhance plant growth, stress tolerance, and pathogen suppression through improved nutrient uptake and metabolite production. PGPR boost phytohormones (IAA, gibberellins, cytokinins, ABA) and secondary metabolites (flavonoids, phenolics, siderophores), strengthening plant defenses. Osmoprotectants like proline, trehalose, and glycine betaine help mitigate drought and salinity stress. PGPR also aid in bioremediation and produce ammonia (NH₃), hydrogen cyanide (HCN), and catalase, supporting root growth and resilience. By enhancing crop yield and reducing environmental pollution, PGPR play a key role in sustainable agriculture. This review examines PGPM, focusing on plant growth-promoting bacteria (PGPB), and highlights future research on microbial strains with enhanced metabolite production for stress mitigation.

Keywords: PGPM; biofertilizers; PGPR; sustainable agriculture; soil health; phytohormones; crop yield enhancement.

1. INTRODUCTION

The global demand for sustainable agricultural practices is intensifying as the world's population continues to grow, projected to reach nearly 10 billion by 2050. This rapid population increase is placing unprecedented pressure on agricultural systems to produce sufficient food while conserving environmental resources (Schneider et al., 2020). However, conventional farming practices, which often rely heavily on chemical fertilizers, pesticides, and intensive irrigation, have led to significant challenges, including soil degradation, loss of biodiversity, and environmental pollution. Current estimates suggest that up to one-third of the world's arable land is degraded, manifesting as nutrient depletion, erosion, salinization, and loss of soil structure (Li et al., 2024). Moreover, the excessive use of chemical fertilizers has not only contributed to the depletion of essential soil nutrients but also caused serious environmental problems, including water contamination, greenhouse gas emissions, and the destruction of beneficial microbial ecosystems (Ngalimat et al., 2021). These issues underscore the need for innovative, sustainable agricultural solutions that maintain high levels of crop productivity while enhancing the long-term health of soils and ecosystems. In this context, biofertilizers, particularly those based on Plant Growth-Promoting Microorganisms (PGPM), have emerged as a promising alternative (Liu et al., 2022). Plant Growth-Promoting Microorganisms (PGPM) are naturally occurring soil microorganisms that form symbiotic relationships

with plants, promoting growth through various mechanisms (Shang et al., 2024). PGPMs function as microbial inoculants that enhance plant nutrient acquisition, produce growth-promoting phytohormones, suppress pathogens, and improve plant resilience to abiotic stresses. They include a diverse group of bacteria, fungi, and other microorganisms such as *Rhizobium*, *Azospirillum*, *Pseudomonas*, and mycorrhizal fungi (Chen et al., 2023). These microorganisms are widely recognized for their ability to improve nutrient cycling, especially through nitrogen fixation and phosphate solubilization. They enhance root growth and development, enabling plants to access nutrients and water more efficiently (Arouna et al., 2023). In addition, PGPMs contribute to disease suppression by outcompeting harmful pathogens, producing antimicrobial compounds, and inducing systemic resistance in plants. As biofertilizers, PGPMs not only boost plant productivity but also play a critical role in restoring soil health by increasing microbial diversity and improving soil structure (Hajjar et al., 2023). The use of PGPM-based biofertilizers offers a sustainable alternative to synthetic fertilizers, which are often associated with environmental degradation and long-term soil health issues (Gogoi et al., 2024). Biofertilizers, by leveraging natural microbial processes, reduce the need for chemical inputs, thereby minimizing the negative environmental impacts of conventional farming practices. PGPMs enhance nutrient availability in the soil, improve water retention, and contribute to overall soil fertility, leading to improved crop yields in a sustainable manner (Radha et al., 2023). This

review focuses on the role of PGPM as microbial inoculants and biofertilizers in sustaining crop productivity and soil health. It examines the mechanisms through which PGPMs promote plant growth, evaluates the latest advancements in PGPM application, and addresses the challenges faced in translating laboratory findings into consistent field results (Dou et al., 2024). Furthermore, the review explores future prospects for PGPM-based biofertilization, highlighting the potential of these microorganisms in driving the shift towards more sustainable and resilient agricultural practices. By analyzing recent research and innovations, this paper aims to provide a comprehensive overview of PGPM's role in promoting sustainable agriculture and ensuring long-term food security (Weifeng et al., 2022).

2. NUTRIENT ACQUISITION

Plant Growth-Promoting Microorganisms (PGPM) play a crucial role in enhancing nutrient availability to plants by facilitating key nutrient acquisition processes such as nitrogen fixation, phosphate solubilization, and potassium mobilization (Saber Kamarpashti et al., 2024). Nitrogen fixation by PGPMs like *Rhizobium* and *Azospirillum* enables the conversion of atmospheric nitrogen into ammonia, which plants can readily absorb. Symbiotic nitrogen-fixing bacteria, such as *Rhizobium* in legume root nodules, and free-living nitrogen fixers like *Azospirillum* provide an eco-friendly alternative to synthetic fertilizers, reducing the environmental impact of excessive nitrogen application (Ma et al., 2024; Rios-Ruiz et al., 2020). Similarly, phosphate-solubilizing bacteria (PSB) like *Pseudomonas* and *Bacillus* secrete organic acids, such as gluconic and citric acid, which solubilize inorganic phosphate, making phosphorus more accessible for plant uptake. Phosphorus is vital for energy transfer, root development, and overall plant vigor (Rios-Ruiz et al., 2024). Additionally, certain strains of *Bacillus* and *Pseudomonas* aid in potassium mobilization from soil minerals, improving enzymatic activity, water regulation, and disease resistance in plants. This process enhances plant nutrition and stress resilience, particularly in potassium-deficient soils, thereby boosting crop productivity (Thepbandit & Athinuwat, 2024).

3. PHYTOHORMONE PRODUCTION

Another vital mechanism by which PGPMs promote plant growth is through the production of phytohormones, which are natural plant growth regulators, including auxins, gibberellins, cytokinins, and ethylene. These hormones influence root and shoot development, cell division, and stress responses (Gui et al., 2023). PGPMs like *Azospirillum* and *Pseudomonas* produce auxins, such as indole-3-acetic acid (IAA), which stimulate root elongation and branching, leading to an improved root system architecture that enhances water and nutrient absorption (Iqbal et al., 2023). Additionally, some PGPMs secrete gibberellins, which promote cell elongation and division, resulting in increased plant height, leaf expansion, and seed germination. For example, *Azospirillum* species have been shown to produce gibberellins that enhance shoot growth and development (Li et al., 2023). Certain PGPMs also produce cytokinins, which regulate cell division, promote shoot formation, delay leaf senescence, and enhance lateral bud growth and nutrient mobilization, particularly under nutrient-limited conditions (Ajjah et al., 2023).

4. BIOCONTROL AND DISEASE SUPPRESSION

PGPMs contribute significantly to plant health by acting as biocontrol agents, suppressing plant pathogens through various mechanisms, including competition, production of antimicrobial compounds, and induced systemic resistance (ISR) (Jin et al., 2024). They compete for nutrients and space, as seen in *Pseudomonas* and *Bacillus*, which outcompete pathogenic microorganisms in the rhizosphere, preventing the establishment and spread of harmful pathogens (Jalal et al., 2024). Additionally, many PGPMs produce antimicrobial compounds such as antibiotics, enzymes, or secondary metabolites that inhibit pathogen growth (Danesh et al., 2024). For example, *Trichoderma* species produce antifungal compounds, while *Pseudomonas fluorescens* secretes siderophores that deprive pathogens of iron, a crucial nutrient for their survival (De-Andrade et al., 2023). Furthermore, PGPMs enhance plant defense through ISR by triggering immune responses mediated by signaling molecules like jasmonic acid and ethylene, equipping plants with improved resistance against future pathogen attacks (Redondo-Gomez et al., 2023).



Fig. 1. Role of PGPMs in various aspects of plant growth and development

5. STRESS TOLERANCE

In addition to improving nutrient acquisition and disease suppression, PGPMs also enhance plant resilience to various abiotic stresses, including drought, salinity, and temperature extremes (Kumar et al., 2022). Under water-limited conditions, PGPMs such as *Azospirillum* and *Pseudomonas* help plants maintain water balance by improving root system architecture, enhancing water uptake, and producing exopolysaccharides that retain moisture around the root zone (Prusty et al., 2023). High salinity in soil can lead to ion toxicity and osmotic stress, impairing plant growth; however, PGPMs mitigate these effects by producing osmoprotectants like proline and glycine betaine, which help plants maintain cellular osmotic balance. Additionally, they improve ionic regulation by aiding in the exclusion or sequestration of harmful ions such as sodium (Wiggins et al., 2022). Temperature extremes, whether hot or cold, can adversely affect plant metabolism, but PGPMs assist in coping with these stresses by producing heat-shock or cold-stress proteins that stabilize cellular functions. Moreover, some PGPMs regulate the production of antioxidants, protecting plants from oxidative stress caused by temperature fluctuations (Abbas et al., 2024).

6. TYPES OF PGPM USED AS BIOFERTILIZERS

Nitrogen-Fixing Bacteria: Nitrogen is a critical nutrient for plant growth, and nitrogen-fixing bacteria play an essential role in converting atmospheric nitrogen (N_2) into ammonia (NH_3), a form that plants can assimilate. This biological nitrogen fixation reduces the need for synthetic nitrogen fertilizers, which are energy-intensive to produce and can cause environmental pollution. Several genera of nitrogen-fixing bacteria, including *Rhizobium*, *Azotobacter*, and *Azospirillum*, are widely used as biofertilizers. *Rhizobium* species are symbiotic nitrogen-fixing bacteria that form nodules on the roots of leguminous plants, where they convert atmospheric nitrogen into ammonia through the enzyme nitrogenase. This symbiotic relationship provides a continuous nitrogen supply, enhancing the growth, yield, and protein content of crops like soybeans, peas, and beans. In contrast, *Azotobacter* species are free-living nitrogen-fixing bacteria found in the rhizosphere of various plants, including cereals and vegetables. Unlike *Rhizobium*, they do not require a specific host and also produce plant growth-promoting substances such as vitamins and phytohormones like auxins, further enhancing plant development. *Azospirillum*

species are associative nitrogen-fixers that colonize the root surface of non-leguminous crops, particularly cereals like wheat, maize, and rice. Besides nitrogen fixation, *Azospirillum* improves root development, leading to better nutrient and water absorption, which contributes to increased crop yield and stress tolerance. Due to their multiple benefits, nitrogen-fixing bacteria serve as valuable biofertilizers for sustainable agriculture.

Phosphate-Solubilizing Bacteria: Phosphorus is an essential macronutrient for plants, playing a crucial role in energy transfer, photosynthesis, and root development. However, much of the phosphorus in soil exists in insoluble forms, making it unavailable to plants (Veldez-Nunez et al., 2020). Phosphate-solubilizing bacteria (PSB), particularly species from the genera *Bacillus* and *Pseudomonas*, can convert these insoluble phosphates into soluble forms that plants can absorb (Ramos et al., 2020). *Bacillus* species are well-known phosphate solubilizers, secreting organic acids such as gluconic acid and citric acid to dissolve calcium phosphate and other insoluble phosphate compounds, thereby enhancing phosphorus availability (Ning et al., 2024). Additionally, *Bacillus* species promote plant growth by producing phytohormones and biocontrol agents that suppress soil-borne pathogens, making them widely used in biofertilizers to improve phosphorus uptake and overall soil health (Mishra et al., 2024). Similarly, *Pseudomonas* species, particularly *Pseudomonas fluorescens*, release various organic acids and enzymes that break down insoluble phosphates (Valdiviezo-Saavedra et al., 2024). Beyond their role in nutrient solubilization, *Pseudomonas* species contribute to plant protection by producing secondary metabolites that suppress fungal pathogens and induce systemic resistance, making them valuable for integrated pest and nutrient management strategies (Quazi et al., 2024).

Mycorrhizal Fungi: Mycorrhizal fungi form mutualistic relationships with plant roots, playing a crucial role in enhancing nutrient and water uptake, especially under nutrient-poor conditions. The most studied group of mycorrhizal fungi in agriculture is the arbuscular mycorrhizal fungi (AMF) (Ngalimat et al., 2023). AMF penetrate plant root cells, forming arbuscules that facilitate nutrient exchange between the fungi and the host plant. By developing an extensive hyphal network in the soil, AMF significantly increase the surface area of the root system, enhancing the

absorption of essential nutrients, particularly phosphorus and micronutrients like zinc and copper (Khaskheli et al., 2020). Additionally, AMF improve water uptake, aiding plant survival in drought-prone areas. Beyond nutrient and water absorption, they contribute to soil structure by producing glomalin, a glycoprotein that binds soil particles, enhancing soil aggregation and stability (Islam et al., 2024).

Other Microbial Inoculants: In addition to nitrogen-fixing and phosphate-solubilizing bacteria, as well as mycorrhizal fungi, other microbial inoculants are gaining recognition for their ability to promote plant growth, suppress diseases, and enhance soil health. Among them, *Trichoderma* spp. and *Bacillus subtilis* are widely studied for their beneficial effects. *Trichoderma* species are beneficial fungi known for their strong biocontrol properties, producing a wide range of enzymes and secondary metabolites that inhibit harmful pathogens such as *Fusarium*, *Rhizoctonia*, and *Sclerotinia* (Rai et al., 2019). Beyond biocontrol, *Trichoderma* enhances plant growth by colonizing the rhizosphere, improving nutrient uptake, and stimulating plant defense mechanisms, making it a valuable biofertilizer for sustainable agriculture (Bauenova et al., 2024). Similarly, *Bacillus subtilis* is a versatile bacterium recognized for promoting plant growth and suppressing plant diseases through the production of antimicrobial compounds, enzymes, and volatile organic compounds (Chittapun et al., 2024). Its ability to form endospores enables survival in harsh environmental conditions, ensuring its efficacy as a biofertilizer. By improving soil health and promoting nutrient cycling, *Bacillus subtilis* enhances plant resilience and productivity, making it an essential component of integrated pest management (IPM) systems (Kumar et al., 2021).

7. PGPM IN SOIL FERTILITY MANAGEMENT

Enhancing Soil Nutrient Cycling: Plant Growth-Promoting Microorganisms (PGPM) play a vital role in enhancing soil fertility by facilitating nutrient cycling, particularly in the carbon, nitrogen, and phosphorus cycles. In the carbon cycle, PGPMs contribute to the decomposition of organic matter, releasing nutrients back into the soil while promoting the formation of stable organic compounds like humus, which enriches soil fertility, improves soil structure, and enhances water retention (Schneider et al.,

2020). Their activity also boosts microbial biomass, providing a continuous source of nutrients for plants upon decomposition (Li et al., 2024). In the nitrogen cycle, PGPMs significantly impact nitrogen availability through nitrogen fixation and nitrification. Nitrogen-fixing bacteria such as *Rhizobium* and *Azospirillum* convert atmospheric nitrogen into ammonia, which is further transformed into nitrate by nitrifying bacteria, ensuring a steady supply of bioavailable nitrogen for plant uptake (Liu et al., 2022). Additionally, PGPMs stimulate soil microbial activity, further enhancing nitrogen availability (Ngalimat et al., 2021). Similarly, in the phosphorus cycle, phosphate-solubilizing bacteria (PSB) like *Bacillus* and *Pseudomonas* convert insoluble phosphorus into soluble forms, making it more accessible to plants and improving overall growth and yield (Shang et al., 2024). By facilitating the efficient cycling of essential nutrients, PGPMs ensure optimal plant growth while maintaining soil health and sustainability in agroecosystems (Chen et al., 2023; Arouna et al., 2023).

Improving Soil Structure and Organic Matter

Content: PGPMs significantly contribute to improving soil structure and increasing organic matter content, both of which are critical for maintaining soil fertility. These microorganisms aid in the decomposition of organic materials, leading to an increase in soil organic matter,

which enhances fertility and serves as a food source for other soil organisms. Their metabolic activities produce various organic compounds that not only enrich the soil but also play a vital role in carbon sequestration, helping to mitigate climate change impacts (Hajjar et al., 2023). Additionally, PGPMs promote soil aggregation through the production of exopolysaccharides and biofilms, improving soil structure by enhancing aeration, water infiltration, and root penetration. Well-aggregated soils are less prone to erosion and compaction, supporting healthier root development and better nutrient uptake (Gogoi et al., 2024). Furthermore, PGPMs contribute to increased microbial diversity, which is essential for the resilience and stability of soil ecosystems. A diverse microbial community enhances nutrient cycling, improves soil health, and strengthens the soil's ability to adapt to environmental changes, ultimately promoting sustainable agricultural practices (Radha et al., 2023; Dou et al., 2024).

Restoring Degraded Soils: Microbial inoculants, including PGPMs, play a crucial role in rehabilitating degraded or nutrient-depleted soils by reintroducing beneficial microorganisms lost due to unsustainable agricultural practices (Weifeng et al., 2022). Degraded soils often lack the diversity and abundance of microorganisms necessary for healthy soil function, but PGPMs

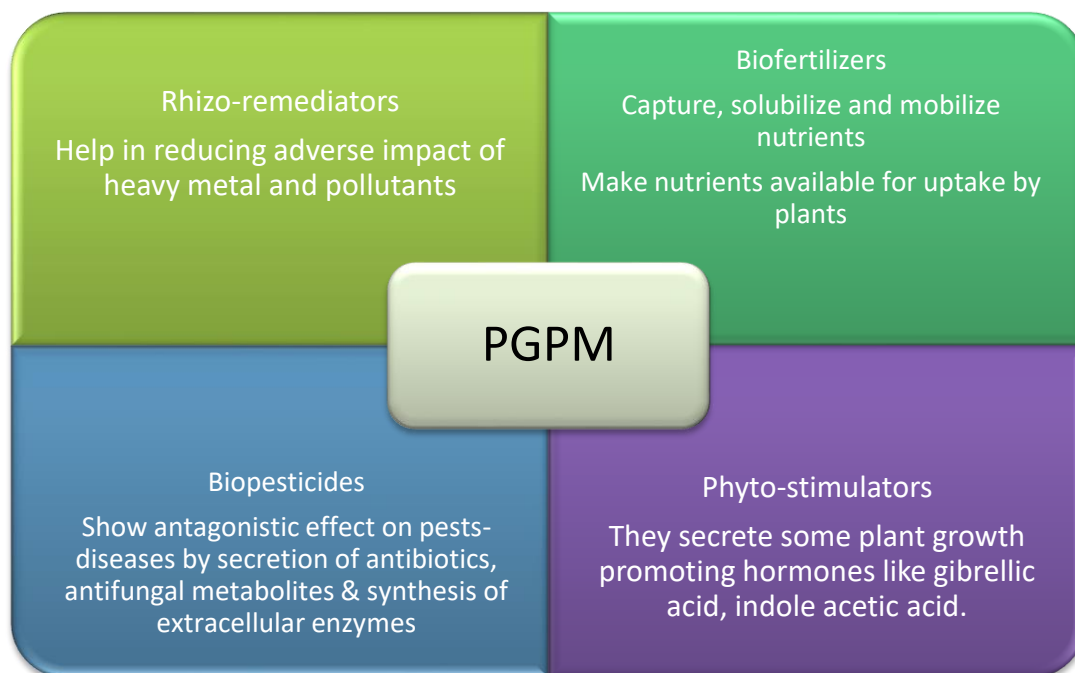


Fig. 2. Environmental and agronomic applications of PGPMs

can restore these microbial communities as biofertilizers (Saberikumarpshiti et al., 2024). For example, nitrogen-fixing bacteria replenish nitrogen levels, while phosphate-solubilizing bacteria improve phosphorus availability (Ma et al., 2024). By enhancing nutrient cycling, organic matter decomposition, and microbial diversity, PGPMs contribute to soil fertility restoration, creating a more balanced and productive ecosystem (Ríos-Ruiz et al., 2023). Additionally, their application aids in soil structure recovery, increasing resilience against erosion and other forms of degradation. As microbial activity improves soil health, plant growth is supported, leading to a self-sustaining ecosystem (Thepdandit & Athinuwat, 2024). Through the strategic use of PGPMs, degraded and nutrient-depleted soils can be revitalized, fostering sustainable agricultural practices and enhancing overall ecosystem health.

Reducing Reliance on Chemical Fertilizers:

The use of Plant Growth-Promoting Microorganisms (PGPM) as biofertilizers significantly reduces the need for synthetic fertilizers in agricultural practices (Gui et al., 2023). This shift towards biological nutrient sources offers multiple benefits, including minimizing environmental pollution, enhancing soil health, and improving cost-effectiveness. Chemical fertilizers, while effective in boosting crop yields, often contribute to environmental issues such as water pollution and soil degradation (Iqbal et al., 2023). Runoff from fertilized fields can lead to eutrophication, causing harmful algal blooms and deteriorating aquatic ecosystems. PGPM-based biofertilizers naturally provide essential nutrients, reducing chemical runoff and protecting water quality and biodiversity (Li et al., 2023). Additionally, continuous reliance on synthetic fertilizers can disrupt natural microbial communities in the soil, leading to diminished fertility over time (Ajijah et al., 2023). PGPMs help restore these communities, promoting a balanced ecosystem that supports nutrient cycling and improves soil structure, ultimately fostering resilient agricultural systems capable of sustaining productivity without excessive chemical inputs (Jin et al., 2024). Furthermore, by decreasing dependence on synthetic fertilizers, farmers can lower input costs, making biofertilizers a more economically viable alternative, particularly when considering the environmental costs associated with chemical fertilizers (Jalal et al., 2024).

Supporting Organic Farming: PGPM biofertilizers are particularly relevant in organic and low-input farming systems, where the use of synthetic fertilizers is restricted or prohibited. Organic farming emphasizes sustainable nutrient management by relying on natural inputs to maintain soil fertility and plant health (Danesh et al., 2024). PGPMs provide an eco-friendly alternative by enhancing nitrogen fixation, phosphorus solubilization, and overall soil health, aligning with the principles of organic agriculture that promote biodiversity and environmental stewardship (De-andrade et al., 2023). In addition to improving soil health, PGPMs contribute to crop quality by enhancing nutrient content and increasing resilience to diseases and pests, leading to higher-quality produce that meets organic standards (Redondo-Gomez et al., 2023). Furthermore, the application of PGPMs supports long-term soil fertility by increasing organic matter content and microbial diversity, ensuring sustainable productivity for future generations (Kumar et al., 2022).

Mitigating Greenhouse Gas Emissions: The application of PGPM-based biofertilizers holds significant potential for reducing greenhouse gas emissions, particularly those associated with nitrogen-based synthetic fertilizers. Nitrous oxide (N_2O), a potent greenhouse gas, is primarily released through microbial processes such as nitrification and denitrification during the application of nitrogen fertilizers (Prusty et al., 2023). By utilizing PGPMs that enhance nitrogen cycling and improve plant nitrogen uptake, the reliance on synthetic nitrogen fertilizers is reduced, thereby lowering overall N_2O emissions (Wiggins et al., 2022). Additionally, PGPMs contribute to carbon sequestration by promoting microbial activity that enhances organic matter decomposition and the formation of stable humic compounds, effectively storing carbon in the soil and mitigating climate change impacts (Abbas et al., 2024). Furthermore, integrating PGPMs into agricultural practices fosters sustainable and resilient farming methods, reducing dependence on fossil fuel-derived fertilizers while enhancing soil health and biodiversity, ultimately supporting long-term environmental sustainability (Habibi et al., 2023; Pieterse et al., 2021).

8. CHALLENGES IN PGPM APPLICATION AND FIELD PERFORMANCE

Inconsistency in Field Performance: One of the primary challenges in the application of

PGPMs is the variability in their performance across different environmental and soil conditions. Environmental factors such as temperature, moisture, pH, and light can significantly influence the efficacy of PGPMs. Certain bacteria may thrive within specific temperature ranges but become less effective under extreme heat or cold, while fluctuations in soil moisture can impact microbial activity, leading to inconsistent results across different growing seasons (Siddika et al., 2024). Additionally, soil characteristics, including texture, structure, organic matter content, and nutrient availability, play a crucial role in PGPM performance. For instance, clayey soils may restrict root penetration and limit microbial colonization, whereas sandy soils may dry out too quickly, hindering microbial survival (Chompa et al., 2024). Consequently, PGPM effectiveness can vary widely depending on the local soil environment, making it difficult to predict outcomes across diverse agricultural settings (Jiang et al., 2024).

Formulation and Delivery: Developing effective formulations and delivery systems for PGPM inoculants presents several challenges that impact their adoption and efficacy. PGPMs can be formulated in various forms, such as liquid, granular, or encapsulated, each with its own advantages and limitations (Janaki et al., 2024). While liquid formulations are easier to apply, they often have shorter shelf lives, whereas granular formulations can offer prolonged release but require specific application techniques. Striking the right balance between efficacy, stability, and user-friendliness is crucial for successful product development (Valdez-Nunez et al., 2020). Additionally, the method of application significantly influences PGPM effectiveness, as traditional approaches like seed coating or soil drenching may result in uneven distribution and inconsistent root colonization (Ramos et al., 2020). To address this, advanced delivery systems, such as controlled-release formulations and encapsulated PGPMs, are being explored; however, further research and development are needed to optimize their performance under field conditions (Ning et al., 2024).

Survival and Colonization in Soil: The survival, colonization, and persistence of PGPMs in the rhizosphere are critical for their success as biofertilizers and are influenced by various factors. The rhizosphere is a dynamic environment teeming with native microbial populations, and when PGPMs are introduced,

they must compete with these established microorganisms for resources and space. If native microbes are more efficient in utilizing available nutrients, PGPMs may struggle to establish and maintain their populations (Mishra et al., 2024; Valdiviezo-Saavedra et al., 2024). Additionally, environmental stressors such as drought, salinity, and soil acidity can negatively impact the survival and activity of PGPMs, leading to a decline in microbial populations and hindering their ability to colonize plant roots effectively (Quazi et al., 2024; Naglimat et al., 2023). Another crucial factor is the composition of root exudates secreted by plants, which play a significant role in attracting and supporting beneficial microbes. Variability in exudate composition among different plant species can affect the colonization success of specific PGPMs, posing challenges for their application in mixed cropping systems (Khaskheli et al., 2020; Islam and Mandal, 2024).

Regulatory and Commercial Barriers: Recent advancements in the formulation of PGPM-based products are crucial for improving their stability, efficacy, and ease of use. Encapsulation technologies protect PGPMs from environmental stressors, such as UV radiation and desiccation, enhancing their survival during storage and application (Shang et al., 2024). These techniques also enable the controlled release of microorganisms, ensuring their viability and activity in the rhizosphere over extended periods (Chen et al., 2023). Similarly, innovations in controlled-release systems allow for the gradual delivery of PGPMs, synchronizing their activity with plant nutrient uptake (Arouna et al., 2023). By aligning microbial activity with plant growth stages, these systems improve nutrient efficiency and reduce the overall quantity of biofertilizers needed. Ongoing research in this area continues to enhance the practicality and effectiveness of PGPM applications across diverse agricultural settings (Hajjar et al., 2023).

9. FUTURE PROSPECTS AND RESEARCH GAPS

Advances in Biotechnology: Emerging biotechnological tools are transforming the development of Plant Growth-Promoting Microorganism (PGPM) strains, enhancing their effectiveness as biofertilizers. Advances in genetic engineering enable the modification of PGPM strains to improve nitrogen fixation, nutrient solubilization, and stress tolerance by identifying and manipulating specific genes

responsible for these functions (Schneider et al., 2020). This innovation allows for the creation of superior strains tailored to diverse environmental conditions, leading to more resilient and effective biofertilizers for specific crops and soils (Li et al., 2024). Additionally, synthetic biology offers a groundbreaking approach to designing and constructing microbial communities with enhanced capabilities (Naglimat et al., 2021). By engineering custom microbial consortia that synergistically promote plant growth, researchers can optimize nutrient uptake and disease resistance, revolutionizing biofertilizer development and application in agriculture (Liu et al., 2022).

Formulation Innovation: Recent advancements in the formulation of PGPM-based products are crucial for improving their stability, efficacy, and ease of use. Encapsulation technologies protect PGPMs from environmental stressors such as UV radiation and desiccation, enhancing their survival during storage and application (Shang et al., 2024). These techniques also enable controlled release, ensuring that microorganisms remain viable and active in the rhizosphere over extended periods (Chen et al., 2023). Additionally, innovations in controlled-release systems allow for the gradual delivery of PGPMs, synchronizing their activity with plant nutrient uptake (Arouna et al., 2023). By aligning microbial activity with plant growth stages, these systems improve nutrient efficiency and reduce the overall quantity of biofertilizers required. Ongoing research in this area continues to enhance the practicality and effectiveness of PGPM applications in diverse agricultural settings (Hajjar et al., 2023).

Precision Agriculture and PGPM: Recent advancements in the formulation of PGPM-based products are crucial for improving their stability, efficacy, and ease of use. Encapsulation technologies protect PGPMs from environmental stressors like UV radiation and desiccation, enhancing their survival during storage and application while also enabling controlled release, ensuring prolonged viability and activity in the rhizosphere (Shang et al., 2024; Chen et al., 2023). Similarly, innovations in controlled-release systems allow for the gradual delivery of PGPMs, synchronizing their activity with plant nutrient uptake and optimizing microbial interactions with plant growth stages (Arouna et al., 2023). By improving nutrient efficiency and reducing the overall quantity of biofertilizers needed, these advancements enhance the

practicality and effectiveness of PGPM applications across diverse agricultural settings, paving the way for more sustainable and efficient crop production (Hajjar et al., 2023).

Long-Term Field Studies: To fully understand the potential of PGPMs as biofertilizers, there is a pressing need for more long-term, large-scale field trials. These studies can provide valuable insights into the efficacy of PGPM applications across various agroecological zones, helping determine optimal conditions for microbial performance, evaluating their impact on crop yields, and assessing changes in soil health over time (Weifeng et al., 2022; Saberi-Kamarposhti et al., 2024). Additionally, assessing the scalability of PGPM applications is crucial for promoting their adoption in diverse agricultural systems. Large-scale trials can help identify best practices for implementation, evaluate economic viability, and develop guidelines for farmers to maximize the benefits of PGPM-based biofertilizers (Ma et al., 2024). Moreover, long-term studies are essential for understanding the broader environmental impacts of PGPM applications, including their influence on soil carbon sequestration, biodiversity, and ecosystem health, thereby contributing to a more sustainable agricultural framework (Thepbandit and Athinuwat, 2024; Rios-Ruiz et al., 2020).

10. CONCLUSION

Plant Growth-Promoting Microorganisms (PGPMs) represent a transformative approach to sustainable agriculture, offering numerous benefits that enhance both crop productivity and soil health. These beneficial microorganisms play a critical role in nutrient acquisition, improve soil structure, and promote resilience against biotic and abiotic stresses. By reducing reliance on synthetic fertilizers, PGPMs help mitigate environmental impacts, such as water pollution and greenhouse gas emissions, thereby fostering a more sustainable agricultural framework.

Despite their potential, several challenges remain in the application of PGPMs. Inconsistencies in field performance, formulation and delivery issues, and factors affecting microbial survival in diverse soil conditions need to be addressed through ongoing research and development. It is crucial to develop innovative formulations, improve microbial strains through biotechnological advancements, and conduct long-term field studies to assess efficacy and scalability across different agroecological zones.

As we look to the future, biofertilizers, particularly PGPMs, will play an increasingly vital role in addressing global food security challenges while promoting environmental sustainability. By integrating these natural solutions into modern agricultural practices, we can create resilient food systems that not only meet the demands of a growing population but also protect and enhance our planet's health. The path forward lies in harnessing the power of PGPMs, ultimately contributing to a sustainable and productive agricultural landscape for generations to come.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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