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Insight on the Role of PGPR in Sustainable Agriculture and Environment-Review of Literature

Biniyam Abdissa Gemeda, Saba Kifle Mulugeta, Tsehay Getachew Mulatu and Teklay Asgedom Teferi*

Manufacturing Industry Development Institute Leather (MIDI); Leather and Leather Products Industry Research Development Center (LLPIRDC), Ethiopia

ABSTRACT

The intensification of agriculture to meet global food demands has exerted tremendous pressure on soil health and ecosystem stability, necessitating a shift towards sustainable practices. Plant Growth-Promoting Rhizobacteria (PGPR), a diverse group of beneficial soil bacteria colonizing the rhizosphere, has emerged as a pivotal tool in this transition. This review synthesizes current literature to provide a comprehensive insight into the multifaceted role of PGPR. It elucidates the direct mechanisms through which PGPR enhance plant productivity, including biological nitrogen fixation, phosphate solubilization, siderophore production, and phytohormone modulation. Furthermore, it examines indirect biocontrol activities, such as the induction of systemic resistance (ISR) and antagonism against phytopathogens via antibiotics and lytic enzymes. Beyond plant growth, the review highlights the critical environmental roles of PGPR in soil remediation, detailing their capacity for heavy metal detoxification and hydrocarbon degradation in contaminated sites.

The integration of PGPR in agroecosystems contributes significantly to soil fertility enhancement, reduction of synthetic inputs, and mitigation of abiotic stress (e.g., drought, salinity). Despite their potential, challenges in bioformulation development, field consistency, and compatibility with agronomic practices remain. This analysis concludes that harnessing PGPR through advanced microbiome engineering and consortium applications is fundamental to developing resilient and sustainable agricultural systems, ensuring food security while preserving environmental integrity.

***Corresponding author**
Teklay Asgedom Teferi, Manufacturing Industry Development Institute Leather(MIDI); Leather and leather Products Industry Research Development Center (LLPIRDC), Ethiopia.

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Introduction

The burgeoning global population, projected to reach 9.7 billion by 2050, presents a formidable challenge to agricultural systems: the imperative to enhance crop productivity amidst escalating environmental degradation and climate change (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Conventional agricultural intensification, heavily reliant on synthetic chemical fertilizers and pesticides, has precipitated significant ecological costs, including soil erosion, water contamination, loss of biodiversity, and greenhouse gas emissions [1]. This paradox has catalyzed a paradigm shift towards sustainable agricultural practices that can reconcile food security with environmental stewardship. In this context, Plant Growth-Promoting Rhizobacteria (PGPR) a diverse group of beneficial soil bacteria colonizing the rhizosphere has emerged as a cornerstone of innovative and ecological solutions. PGPR facilitate plant growth and development through a multitude of direct and indirect mechanisms, including biological nitrogen fixation, phosphate and potassium solubilization, phytohormone production (e.g., auxins, cytokinins, gibberellins), and induction of systemic resistance against phytopathogens [2-3]. Their application extends beyond productivity, contributing to soil health restoration, bioremediation of contaminated sites, and mitigation of abiotic stresses like drought and salinity, thereby positioning them as vital agents for environmental sustainability [4].

Objectives

This review aims to synthesize and critically evaluate the existing body of literature on PGPR to provide a comprehensive insight into their multifaceted roles. The specific objectives are:

- To delineate the primary direct and indirect mechanisms employed by PGPR in promoting plant growth, health, and yield, as elucidated in key studies [3-5].
- To analyze the documented contributions of PGPR applications to the principles of sustainable agriculture, including their role in reducing dependency on agrochemicals, enhancing nutrient use efficiency, and improving soil fertility and structure.
- To assess the environmental biotechnology applications of PGPR, focusing on their efficacy in phytoremediation and rhizoremediation of heavy metals and organic pollutants, as explored by researchers like [6].
- To examine the current challenges and limitations hindering the widespread commercialization and field-scale application of PGPR inoculants, addressing issues of formulation, shelf-life, consistency under diverse field conditions, and compatibility with existing farm management practices.
- To identify future research directions and technological innovations, such as the use of omics technologies and

synthetic microbial consortia, that could optimize the selection, formulation, and deployment of PGPR for robust and predictable outcomes in sustainable agriculture and environmental management.

Methodology

This review employed a systematic search strategy to identify, evaluate, and synthesize existing literature regarding Plant Growth-Promoting Rhizobacteria (PGPR) and their impact on agricultural sustainability and environmental health.

Search Strategy and Data Sources

A comprehensive literature search was conducted across major scientific databases, including Web of Science, Scopus, PubMed, and Google Scholar. Key search terms and Boolean operators used included: (“PGPR” OR “rhizobacteria” OR “biofertilizers” OR “biocontrol agents”) AND (“sustainable agriculture” OR “crop yield” OR “soil health” OR “environmental remediation”).

Inclusion and Exclusion Criteria Studies were selected based on the following criteria:

- Inclusion: Peer-reviewed research articles, review papers, and meta-analyses published in English. The content must specifically address the mechanisms of PGPR action, field applications, or environmental impacts (e.g., soil structure, pollutant degradation).
- Exclusion: Conference abstracts, non-peer-reviewed articles, editorials, studies lacking clear methodologies, and duplicate publications.

Data Screening and Extraction

Initial screening involved reviewing titles and abstracts for relevance to the study objectives. Full-text articles of potentially relevant studies were subsequently retrieved and assessed. Data was extracted focusing on key themes: PGPR strains identified, direct and indirect mechanisms of action (e.g., nitrogen fixation, phytohormone production), effects on various crops under stress and non-stress conditions, and environmental benefits.

Data Synthesis

A qualitative, thematic synthesis approach was used to analyze the extracted data. Information was categorized into distinct themes such as nutrient fertilization, phytopathogen control, and abiotic stress tolerance to provide a coherent overview of the current understanding and future prospects of PGPR application in sustainable systems.

Key Roles of PGPR in Sustainable Agriculture

Nutrient Enhancement

Plant Growth-Promoting Rhizobacteria (PGPR) plays several key roles in supporting sustainable agricultural systems, primarily through nutrient enhancement. This function is achieved by facilitating plant nutrient uptake, most notably through biological nitrogen fixation and phosphate solubilization, which directly reduces dependency on synthetic chemical fertilizers [7].

Specifically, genera such as Azotobacter and Azospirillum are renowned for their ability to fix atmospheric nitrogen in non-leguminous crops, a process detailed by as a cornerstone for improving nitrogen use efficiency in agroecosystems [8]. Concurrently, PGPR solubilize insoluble phosphate compounds, making phosphorus a major macronutrient often locked in soils bioavailable to plants. Documented that phosphate-solubilizing bacteria, including strains of Pseudomonas and Bacillus, are critical agents in mobilizing this nutrient, thereby directly contributing to a decreased requirement for manufactured phosphate fertilizers [9]. Together, these mechanisms exemplify how PGPR act as vital biological agents in fostering a more sustainable and productive agriculture [10].

Phytohormone Production

Plant Growth-Promoting Rhizobacteria (PGPR) are integral to sustainable agricultural systems, with one of their key roles being phytohormone production. Specifically, these rhizobacteria synthesize essential phytohormones such as auxins, cytokinins, and gibberellins. This synthesis directly stimulates enhanced root architecture and biomass, promotes seedling vigor and growth, and contributes to significant improvements in overall crop productivity [10-12]. The microbial production of indole-3-acetic acid (IAA), a primary auxin, is particularly well-documented as a mechanism for facilitating plant development and improving stress resilience, thereby reducing dependence on synthetic inputs [13].

Bio Control Agent

Plant Growth-Promoting Rhizobacteria (PGPR) serves as a critical Biocontrol Agent in sustainable agriculture by directly suppressing soil-borne pathogens through competitive exclusion, antibiosis, and parasitism [5]. Furthermore, a key mode of action is the induction of the plant’s own systemic defense mechanisms. PGPR prime the plant’s physiological state, leading to Induced Systemic Resistance (ISR), a phenotypically similar but hormonally distinct pathway from pathogen-induced systemic acquired resistance (SAR). This ISR is primarily mediated by jasmonate and ethylene signaling pathways, enhancing the plant’s capacity to resist subsequent pathogen attack [14]. This dual action direct antagonism and host priming reduces reliance on synthetic pesticides, thereby supporting sustainable crop protection [10].

Stress Tolerance

Plant Growth-Promoting Rhizobacteria (PGPR) plays a pivotal role in enhancing stress tolerance, a cornerstone of sustainable agriculture. Specifically, they mitigate the detrimental effects of abiotic stresses, including salinity, drought, and heavy metal toxicity, through the production and modulation of antioxidant enzymes. For instance, PGPR can induce the synthesis of key enzymes such as catalase (CAT) and peroxidase (POD) within host plants, which actively scavenge reactive oxygen species (ROS) generated under stress conditions, thereby protecting cellular integrity and improving crop resilience [15,16]. This mechanism is crucial for maintaining productivity in marginal environments. Demonstrated that inoculation with Pseudomonas spp [17]. significantly increased the activities of CAT and POD in wheat plants under saline stress, leading to improved biomass and yield. Similarly, documented that drought-stressed maize plants inoculated with Bacillus subtilis exhibited enhanced antioxidant enzyme activity, resulting in better water retention and growth. Furthermore, in the context of heavy metal contamination, [3] has extensively reviewed how PGPR, including strains of Pseudomonas and Bacillus, can reduce metal uptake and alleviate phytotoxicity by bolstering the plant’s endogenous antioxidant defense system [3,18]. Collectively, these microbial-mediated biochemical adaptations underscore the vital role of PGPR in developing climate-resilient and sustainable cropping systems by reducing dependence on chemical inputs and enhancing plant innate stress tolerance [19].

Table: Selected PGPR Genera/Strains, Functions, Mechanisms, and Target Applications

PGPR Genus/Strain	Primary Function(s)	Mechanism of Action	Target Crops/Conditions
Azospirillum brasilense (e.g., Strain Sp7)	Nitrogen fixation & Growth stimulation	Biological Nitrogen Fixation (BNF) via nitrogenase enzyme; production of phytohormones like Indole-3-Acetic Acid (IAA) [20].	Cereals (Maize, Wheat) and grasses; particularly effective under nitrogen-limited soil conditions.
Bacillus subtilis (e.g., Strain QST 713)	Biocontrol & Stress Tolerance	Synthesis of lipopeptides (surfactin, fengycin) that disrupt pathogen membranes; formation of robust biofilms [21].	High-value fruits and vegetables; mitigates salinity and drought stress.
Pseudomonas fluorescens (e.g., Strain Pf-5)	Disease Suppression & Siderophore production	Secretion of antibiotics like 2, 4-diacetylphloroglucinol (DAPG) and iron-chelating siderophores that starve pathogens [22].	Potatoes, sugar beets, and tomatoes; effective against soil-borne fungi like Pythium and Rhizoctonia.
Rhizobium leguminosarum (bv. viciae)	Symbiotic Nitrogen Fixation	Formation of root nodules; conversion of atmospheric N2 into ammonia (NH3) directly accessible to the host [23].	Legumes (Peas, Lentils, Faba beans); essential for sustainable protein crop production.
Pseudomonas putida (e.g., Strain KT2440)	Phosphate Solubilization & Phytoremediation	Secretion of organic acids (e.g., gluconic acid) to solubilize inorganic PO43-; degradation of soil pollutants.	Broad-spectrum (Wheat, Soybeans); highly effective in alkaline soils where phosphorus is "locked."

Environmental Benefits and Sustainability

Rhizoremediation

Plant Growth-Promoting Rhizobacteria (PGPR) contribute significantly to environmental sustainability through a process known as rhizoremediation, which is the synergistic use of plants and their associated rhizospheric bacteria to degrade, sequester, or immobilize environmental pollutants in soil. This bioremediation strategy is particularly effective for the restoration of degraded ecosystems contaminated with persistent organic pollutants and toxic elements. Specifically, PGPR enhance the degradation of various pesticides, polycyclic aromatic hydrocarbons (PAHs), and other xenobiotics through the production of catabolic enzymes and biosurfactants [24]. Furthermore, for inorganic contaminants like heavy metals (e.g., lead, cadmium, and arsenic), certain PGPR strains employ mechanisms such as biosorption, precipitation, and enzymatic transformation to reduce metal bioavailability and toxicity, thus facilitating phytostabilization [25].

The sustainability advantage of rhizoremediation lies in its in-situ application, which is often less disruptive and more cost-effective than physical or chemical remediation techniques. By improving soil health and structure, promoting plant growth under stress, and ultimately restoring microbial diversity, PGPR-driven rhizoremediation supports the broader goals of ecological restoration and sustainable land management [19]. This approach aligns with circular economy principles by turning contaminated sites into productive lands, thereby closing environmental loops and reducing the need for external, energy-intensive inputs.

Soil Health Improvement

A core environmental benefit of many sustainable practices, such as the use of cover crops, organic amendments, and conservation tillage, is soil health improvement. These practices enhance soil structure by promoting aggregation and porosity, which improves water infiltration and reduces erosion [26]. Furthermore, they contribute to long-term fertility by increasing soil organic matter, which serves as a reservoir of nutrients and provides energy for soil microorganisms [27]. This biological activation is crucial, as healthy soil microbiomes drive nutrient cycling, suppress pathogens, and enhance plant resilience [28]. Consequently, the systematic improvement of soil health forms the foundation of sustainable, eco-friendly agricultural systems by reducing dependency on synthetic inputs, enhancing ecosystem services, and increasing agroecosystem resilience to climate stressors [29].

Reducing Agrochemical Dependency

The utilization of biological alternatives, such as biopesticides and biofertilizers, plays a significant role in reducing agrochemical dependency. This shift provides effective alternatives to synthetic chemical inputs, which directly reduces environmental contamination by minimizing the leaching and runoff of nutrients and toxic compounds into aquatic and terrestrial systems, thereby protecting ecosystems from eutrophication, biodiversity loss, and soil [30,31].

The sustainability benefits of this reduction are substantial. For instance, the adoption of microbial inoculants and biocontrol agents helps preserve non-target organisms, including vital pollinators and natural pest predators, maintaining essential ecosystem services [32]. Furthermore, the decreased reliance on synthetic nitrogen fertilizers, which are energy-intensive to produce, lowers agriculture's overall carbon footprint and mitigates associated greenhouse gas emissions, such as nitrous oxide (N_2O) [33]. This transition supports the principles of circular economy and agro ecology by leveraging ecological processes for crop production.

Conclusion and Recommendation

Conclusion

The review substantiates that Plant Growth-Promoting Rhizobacteria (PGPR) are pivotal agents in transitioning toward sustainable agricultural and environmental systems. Their multifaceted roles enhancing plant growth via nutrient solubilization and phytohormone production, inducing systemic resistance against pathogens, and ameliorating abiotic stresses directly contribute to increased crop productivity and resilience. Beyond the farm, PGPR play a significant environmental role by facilitating phytoremediation of contaminated soils, reducing the need for synthetic fertilizers and pesticides, and promoting soil carbon sequestration and health. The cumulative evidence confirms that PGPR integration represents a powerful, eco-friendly biotechnology aligned with the core principles of sustainability. However, the transition from robust laboratory results to consistent, large-scale field application remains the central challenge, hindered by ecological variability, formulation hurdles, and a fragmented understanding of plant-microbe-environment interactions [34,35].

Recommendations

To realize the full potential of PGPR, a strategic, multi-pronged approach is necessary:

Strain Selection & Formulation Development

- Prioritize the isolation of host- and climate-specific PGPR consortia (combinations of bacteria) rather than relying on single, universal strains. This enhances adaptability and efficacy under local conditions.
- Invest in advanced formulation technologies (e.g., nano-encapsulation, polymer-based coatings, peat-based carriers) to improve bacterial survival, shelf life, and ease of application for farmers.

Soil-Centric Research & Application

- Adopt a "soil health first" philosophy. Research should focus on how PGPR interact with the native soil microbiome (the microbiome) and organic matter to create synergistic benefits.
- Promote PGPR as a core component of integrated nutrient and pest management (INM & IPM) systems, combining them with organic amendments, reduced chemical inputs, and cover cropping.

Commercialization & Policy Support

- Develop clear regulatory frameworks and quality control standards for PGPR-based biofertilizers and biopesticides to build market and farmer trust.
- Implement government subsidies and incentive programs to lower the cost of high-quality PGPR products for farmers and encourage their adoption.
- Support public-private partnerships to bridge the gap between academic research and commercial product development.

Farmer Engagement & Knowledge Dissemination

- Launch targeted extension programs and demonstration farms to showcase the economic and agronomic benefits of PGPR, providing hands-on learning for farmers.
- Develop clear, multilingual guidelines on the correct storage, application methods, and expected outcomes of PGPR products.

Future Research Directions

- Leverage omics technologies (metagenomics, transcriptomics, and metabolomics) to decode the complex molecular dialogues in the rhizosphere and engineer more effective consortia.
- Investigate the role of PGPR in climate change adaptation, particularly their potential to enhance crop tolerance to drought, salinity, and elevated temperatures.
- Conduct long-term, large-scale field trials across diverse agro-climatic zones to generate robust data on yield impacts, soil health improvements, and economic viability.

Author's Contribution

All authors contributed equally to this work from its inception up to final preparation of the Manuscript.

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Conflicting Interests

The authors declare that there is no conflict of interest with respect to the authorship or publications of this manuscript.

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