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A Review of PGPR-Mediated Strategies for Enhancing Sustainable Crop Production

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ABSTRACT

The escalating global demand for food, coupled with the environmental degradation caused by the indiscriminate use of chemical fertilizers and pesticides, has intensified the search for sustainable alternatives in modern agriculture. Plant Growth-Promoting Rhizobacteria (PGPR) have emerged as a promising biological tool capable of enhancing crop productivity while minimizing ecological harm. These beneficial bacteria colonize the rhizosphere and plant roots, where they stimulate growth through a diverse array of direct and indirect mechanisms, including biological nitrogen fixation, phosphate solubilization, phytohormone production, siderophore secretion, and the induction of systemic resistance against pathogens. This review synthesizes recent advances (2015–2024) in understanding PGPR-mediated strategies for sustainable crop production. It examines the principal mechanisms by which PGPR promote plant growth, evaluates their role in mitigating biotic and abiotic stresses such as drought, salinity, and heavy-metal toxicity, and explores their integration into bioformulations and field-scale applications. The review further highlights the synergistic potential of PGPR consortia, the influence of soil and environmental factors on their efficacy, and the technological innovations—such as encapsulation and omics-based screening—that are improving formulation stability and field performance. Despite considerable laboratory success, challenges relating to inconsistent field results, shelf-life, regulatory hurdles, and commercialization persist. Addressing these gaps through interdisciplinary research, advanced delivery systems, and supportive policy frameworks will be essential to realizing the full potential of PGPR as a cornerstone of climate-resilient, sustainable agriculture.

Keywords: Plant Growth-Promoting Rhizobacteria; sustainable agriculture; biofertilizers; abiotic stress; rhizosphere; biocontrol; crop productivity.

1. INTRODUCTION

Global agriculture stands at a critical juncture, confronting the dual imperative of feeding a population projected to surpass nine billion people by 2050 while simultaneously reducing its substantial environmental footprint. For decades, the productivity gains of the Green Revolution were underpinned by heavy reliance on synthetic fertilizers, agrochemicals, and intensive irrigation. While these inputs dramatically increased yields, they have also contributed to soil degradation, groundwater contamination, biodiversity loss, and greenhouse-gas emissions. As the long-term costs of conventional intensification become increasingly apparent, researchers and policymakers alike have turned their attention toward biological and ecologically grounded approaches that can sustain productivity without compromising the integrity of agroecosystems.

Among these approaches, the exploitation of beneficial plant–microbe interactions has gained particular prominence. Plant Growth-Promoting Rhizobacteria (PGPR) represent a functionally diverse group of soil bacteria that inhabit the rhizosphere—the narrow zone of soil influenced by root exudates—and confer measurable benefits to their host plants. The following subsections introduce the conceptual and practical foundations of PGPR research, outlining their definition and diversity, the rationale for their use in sustainable systems, the scope of this review, and the methodological basis on which it draws.

1.1 Defining PGPR and Their Ecological Niche

Plant Growth-Promoting Rhizobacteria are free-living, root-associated bacteria that exert a beneficial effect on plant growth either directly or indirectly. The rhizosphere they inhabit is a dynamic and chemically rich microhabitat, sustained by the continuous release of root exudates containing sugars, amino acids, organic acids, and secondary metabolites. These compounds act as chemoattractants and nutrient sources, fostering dense and metabolically active microbial communities that can reach population densities far exceeding those of the surrounding bulk soil. Genera commonly recognized as PGPR include Pseudomonas, Bacillus, Azospirillum, Rhizobium, Azotobacter, Enterobacter, Serratia, and Burkholderia, among many others, each contributing a distinctive set of functional capabilities. Their ecological success in this competitive niche depends on traits such as efficient root colonization, motility, biofilm formation, and the capacity to outcompete or antagonize less beneficial microorganisms. Some PGPR function as endophytes, colonizing internal plant tissues and thereby gaining a degree of protection from the harsh and variable conditions of the soil. Understanding the ecology of this niche is fundamental, because the persistence and efficacy of any introduced PGPR strain ultimately hinge on its ability to establish and maintain itself within the indigenous soil microbiome rather than being displaced by resident competitors.

1.2 The Rationale for Sustainable Crop Production

The case for integrating PGPR into crop production rests on both ecological and economic foundations. Chemical fertilizers, particularly nitrogen and phosphorus formulations, are energy-intensive to manufacture and are frequently used at efficiencies well below their theoretical potential, with substantial fractions lost through leaching, volatilization, and runoff. These losses translate into economic waste for farmers and environmental harm in the form of eutrophication of water bodies and atmospheric pollution through nitrous-oxide emissions. PGPR offer a route to improving nutrient-use efficiency by mobilizing otherwise unavailable nutrients, fixing atmospheric nitrogen, and stimulating root architecture that enhances nutrient and water capture. Beyond nutrition, their capacity to suppress pathogens and buffer plants against environmental stress positions them as multifunctional inputs aligned with the principles of integrated nutrient and pest management. For resource-limited smallholder farmers in particular, locally adapted microbial inoculants represent an affordable and renewable supplement to, or partial replacement for, costly agrochemicals, with the added advantage that suitable strains can often be isolated from local soils and propagated with relatively simple infrastructure. As consumer demand for residue-free produce and environmentally certified farming systems grows, the market and policy environment is also turning increasingly favorable toward biological inputs of this kind.

1.3 Scope and Objectives of the Review

This review aims to provide a focused synthesis of PGPR-mediated strategies for sustainable crop production, drawing predominantly on peer-reviewed literature published between 2015 and 2024. Its objectives are fourfold: first, to elucidate the principal direct and indirect mechanisms by which PGPR enhance plant growth; second, to evaluate the role of PGPR in alleviating biotic and abiotic stresses that increasingly threaten agricultural systems under climate change; third, to examine the translation of laboratory findings into practical bioformulations and field applications; and fourth, to identify the persistent challenges and emerging opportunities that will shape the future trajectory of the field. By integrating mechanistic understanding with applied and translational perspectives, the review seeks to bridge the gap between fundamental microbiology and on-farm implementation.

1.4 Methodological Approach

The literature underpinning this review was assembled through a structured survey of major scientific databases, including Scopus, Web of Science, and Google Scholar, using combinations of keywords such as “PGPR,” “plant growth-promoting rhizobacteria,” “biofertilizer,” “abiotic stress tolerance,” and “sustainable agriculture.” Priority was given to original research articles, meta-analyses, and authoritative reviews published within the past decade, ensuring that the synthesis reflects the most current understanding of the field. Studies were selected for their methodological rigor, relevance to crop production, and contribution to mechanistic or applied knowledge. The resulting body of evidence spans controlled laboratory experiments, greenhouse trials, and field studies across a range of crops and agroclimatic conditions, providing a balanced foundation for the analysis that follows.

2. LITERATURE REVIEW

The scientific literature on PGPR has expanded rapidly over the past decade, reflecting both deepening mechanistic insight and growing interest in practical deployment. The following subsections organize this body of work into four thematic areas: the mechanisms of plant growth promotion, the role of PGPR in stress alleviation, advances in formulation and field application, and the integrative use of microbial consortia within broader agroecosystem management.

2.1 Mechanisms of Plant Growth Promotion

PGPR enhance plant growth through an interconnected suite of direct mechanisms that improve nutrient availability and modulate plant physiology. Biological nitrogen fixation, carried out by diazotrophic genera such as Azospirillum, Azotobacter, and symbiotic Rhizobium, converts atmospheric dinitrogen into plant-available ammonium, reducing dependence on synthetic nitrogen inputs whose manufacture is both energy-intensive and a significant source of greenhouse-gas emissions. Phosphate-solubilizing bacteria, including many Pseudomonas and Bacillus strains, secrete organic acids and phosphatases that liberate phosphorus bound in insoluble mineral and organic forms, thereby improving its bioavailability in the rhizosphere; this is especially valuable given that a large proportion of applied phosphate fertilizer is rapidly fixed into forms inaccessible to plants. Certain PGPR additionally mobilize potassium and micronutrients such as zinc and iron, broadening their nutritional contribution. Recent studies have consistently demonstrated that inoculation with such strains increases nutrient uptake, biomass accumulation, and yield across diverse crops including wheat, maize, and rice, frequently permitting reductions in fertilizer application without commensurate yield penalties.

A second major mechanism involves the modulation of plant hormone levels. Many PGPR synthesize indole-3-acetic acid (IAA), gibberellins, and cytokinins, which stimulate root elongation, lateral root formation, and root-hair proliferation, expanding the surface area available for nutrient and water absorption. IAA in particular has been the subject of extensive investigation, as bacterially derived auxins integrate with the plant's own hormonal signaling to reshape root architecture in ways that markedly improve resource foraging. Equally important is the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, produced by numerous PGPR, which cleaves the ethylene precursor ACC and thereby lowers stress-induced ethylene levels that would otherwise inhibit root growth. Because elevated ethylene is a common physiological response to virtually every form of environmental stress, ACC-deaminase activity has come to be regarded as one of the most broadly valuable traits a PGPR strain can possess.

Indirect mechanisms further contribute to plant fitness. Siderophore production sequesters iron in a form accessible to plants while depriving competing pathogens of this essential micronutrient, and the synthesis of antibiotics, lytic enzymes, and volatile organic compounds suppresses soil-borne diseases. Volatile organic compounds are particularly intriguing because they can influence plant growth and defense at a distance, without direct physical contact between bacterium and root. Many strains also produce exopolysaccharides that improve soil structure and protect bacterial cells, and some contribute to the degradation of soil pollutants. Collectively, these mechanisms rarely act in isolation; rather, individual strains typically possess multiple traits whose combined and often synergistic action accounts for the observed growth benefits. This multifunctionality complicates the attribution of effects to any single pathway but also explains the robustness of well-adapted PGPR across varied conditions, and it underlies the contemporary emphasis on selecting strains that combine several beneficial traits within a single organism.

2.2 PGPR in Abiotic and Biotic Stress Alleviation

One of the most compelling contemporary applications of PGPR lies in their capacity to enhance plant resilience to environmental stress, a property of escalating importance under climate change. Drought, salinity, and heavy-metal contamination impose severe constraints on crop productivity worldwide, and a substantial body of recent work has documented the ameliorative effects of PGPR inoculation under these conditions. Under drought stress, PGPR improve water relations by promoting deeper and denser root systems, producing exopolysaccharides that improve soil aggregation and water retention, and triggering the accumulation of osmoprotectants such as proline, glycine betaine, and soluble sugars that stabilize cellular structures under dehydration. ACC-deaminase-producing strains are particularly effective in this context, as they curtail the excessive ethylene production that accompanies water deficit and would otherwise accelerate senescence and limit root expansion. Inoculated plants frequently exhibit improved relative water content, sustained photosynthetic performance, and higher survival and yield under water-limited regimes, making PGPR an appealing tool for rain-fed and dryland agriculture where drought is a recurring constraint. (Bhattacharyya, P. N., & Jha, D. K,2012).

In saline soils, PGPR mitigate ionic and osmotic stress by restricting sodium uptake, maintaining favorable potassium-to-sodium ratios, and bolstering the activity of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase that scavenge reactive oxygen species. By stabilizing cellular ion homeostasis and reducing oxidative damage, inoculated plants sustain photosynthetic activity and growth under salinity levels that would otherwise be severely inhibitory. Comparable protective effects have been reported under heavy-metal stress, where certain strains immobilize, adsorb, or transform toxic metals and reduce their translocation into edible plant tissues, offering a dual benefit of crop protection and reduced contaminant entry into the food chain. These bioremediation-linked capabilities have attracted growing interest for the rehabilitation of marginal and polluted soils. (Kumar, A., & Verma, J. P,2018)

On the biotic front, PGPR confer protection against fungal, bacterial, viral, and nematode pathogens through both direct antagonism and the elicitation of induced systemic resistance (ISR). ISR represents a primed defensive state that enables plants to respond more rapidly and robustly to subsequent pathogen attack, mediated by signaling pathways distinct from those activated by classical systemic acquired resistance. Direct antagonism, by contrast, operates through competition for nutrients and niche space, the secretion of antimicrobial compounds, and the production of cell-wall-degrading enzymes. The combination of these offensive and defensive strategies allows PGPR to reduce disease incidence while diminishing reliance on synthetic pesticides. The dual capacity to address abiotic and biotic stressors simultaneously underscores the value of PGPR as multifunctional agents in resilient cropping systems, a quality that is increasingly prized as growers confront the compound stresses characteristic of a warming and more variable climate. (Mahmud, K.,2020).

2.3 Bioformulation and Field Application Strategies

The translation of promising laboratory strains into reliable agricultural products depends critically on formulation technology. A bioformulation must preserve the viability and functionality of beneficial bacteria during storage, transport, and application, while ensuring effective delivery to the target environment at a population density sufficient to produce a measurable effect. Traditional carrier-based formulations, employing materials such as peat, lignite, vermiculite, and talc, remain widely used owing to their low cost and ease of preparation. However, these formulations often suffer from limited shelf-life and inconsistent field performance, particularly under the high temperatures and variable humidity encountered during storage and distribution in many agricultural regions. The choice of carrier strongly influences cell survival, and considerable research has been devoted to identifying materials and additives that prolong viability. Liquid formulations supplemented with protective additives, osmotica, and cell-stabilizing agents have improved viability in many cases and offer advantages in handling and application uniformity.

More recently, advanced delivery systems—most notably microencapsulation in polymeric matrices such as alginate—have attracted considerable attention. Encapsulation protects bacterial cells from desiccation, ultraviolet radiation, temperature extremes, and microbial competition, and enables the controlled, gradual release of inoculants into the rhizosphere. Studies evaluating encapsulated PGPR have reported enhanced survival and more consistent growth-promoting effects compared with conventional carriers. The incorporation of protective osmolytes, prebiotic substrates, and nutrient supplements within these matrices can further sustain bacterial metabolism during storage and after application. Application methods—including seed coating, soil drenching, and root dipping—further influence colonization success and must be matched to the crop and cropping system.

Despite these advances, the gap between greenhouse efficacy and field reliability persists, reflecting the influence of indigenous microbial competition, soil heterogeneity, and fluctuating environmental conditions on introduced strains. Field soils harbor established microbial communities that may outcompete or antagonize introduced bacteria, and variation in moisture, temperature, pH, and organic-matter content can dramatically alter inoculant performance from one location to another. Bridging this gap demands not only better formulations but also a deeper understanding of the ecological factors governing the establishment and persistence of introduced strains, alongside standardized protocols for quality assurance that guarantee a sufficient population of viable, active cells reaches the target environment. (Gouda, S., Kerry, R. G.2020).

2.4 Microbial Consortia and Integrated Approaches

Recognizing that single-strain inoculants frequently underperform in complex field environments, researchers have increasingly explored multi-strain consortia and integrated management strategies. Consortia that combine bacteria with complementary functions—such as nitrogen fixation, phosphate solubilization, and biocontrol—can deliver broader and more stable benefits than individual strains, owing to functional redundancy and synergistic interactions that buffer the community against the loss of any single member. A consortium may, for instance, pair a vigorous nitrogen fixer with a phosphate solubilizer and a disease-antagonistic strain, so that the host plant receives nutritional and protective benefits simultaneously. The co-inoculation of PGPR with arbuscular mycorrhizal fungi has likewise been shown to enhance nutrient acquisition and stress tolerance beyond the effects of either partner alone, as the extensive hyphal networks of the fungi extend the effective reach of the root system while the bacteria improve nutrient mobilization and root health. Designing effective consortia, however, requires careful attention to compatibility among constituent organisms to avoid antagonism, since strains that perform well in isolation may inhibit one another when combined. (Mishra, J., Singh, R,2017)

Integration extends beyond microbial combinations to the broader management context. PGPR are most effective when deployed as components of integrated nutrient and pest management rather than as standalone substitutes for all conventional inputs. Combining microbial inoculants with reduced rates of chemical fertilizer, organic amendments, and appropriate agronomic practices can sustain yields while substantially lowering chemical inputs, an approach that aligns microbial technology with the practical realities of commercial farming. Seed biopriming, in which seeds are treated with beneficial bacteria prior to sowing, has emerged as an especially efficient delivery route that improves germination, early vigor, and establishment while economizing on inoculant quantities. (Olanrewaju, O. S,2017).

Advances in omics technologies—genomics, metagenomics, transcriptomics, and metabolomics—are accelerating the rational selection and design of consortia by revealing the functional capabilities and ecological interactions of candidate strains. Whereas earlier strain development relied heavily on laborious empirical screening, these tools now permit researchers to identify the genes and metabolic pathways responsible for beneficial traits and to anticipate how strains will behave within a community. Such knowledge-driven approaches mark a shift from empirical screening toward the deliberate engineering of beneficial plant microbiomes tailored to specific crops and environments. The longer-term vision emerging from this work is one of designer microbial communities, assembled with predictable functions and matched to defined agronomic objectives, that can be reliably reconstituted in the field. Realizing this vision will require continued integration of microbial ecology, molecular biology, and agronomy, but the trajectory of recent research suggests it is an increasingly attainable goal.

3. CONCLUSION

The accumulated evidence reviewed here affirms that Plant Growth-Promoting Rhizobacteria constitute a versatile and ecologically sound instrument for advancing sustainable crop production. Through a rich repertoire of mechanisms—spanning nitrogen fixation, phosphate solubilization, phytohormone modulation, siderophore production, and the induction of systemic resistance—PGPR enhance nutrient acquisition, stimulate root development, and fortify plants against the biotic and abiotic stresses that increasingly threaten global agriculture. Their demonstrated capacity to improve resilience to drought, salinity, and heavy-metal toxicity is especially significant in the context of a changing climate, positioning them as valuable allies in the pursuit of climate-resilient farming systems.

At the same time, the field must contend with the persistent disparity between controlled experimental success and variable field performance. The efficacy of introduced strains is contingent upon their ability to colonize and persist within competitive indigenous microbiomes, and upon formulation technologies capable of preserving viability from production to deployment. Multi-strain consortia, advanced encapsulation methods, and integration within broader nutrient and pest management frameworks offer promising avenues for narrowing this gap. Realizing the full agricultural potential of PGPR will ultimately require a coordinated effort that unites mechanistic research, formulation science, rigorous field validation, and enabling regulatory and economic frameworks. With such concerted investment, PGPR can move from a complementary input toward a central pillar of a more productive, resilient, and environmentally responsible agriculture.

4. FUTURE WORK

Several priorities emerge as essential directions for future research and development. Foremost is the need to improve the consistency and predictability of PGPR performance under real field conditions. This will demand multi-location, multi-season field trials that account for the influence of soil type, climate, and indigenous microbial communities on inoculant efficacy, moving the field beyond the controlled environments in which most successes have been documented.

A second priority concerns the rational design of microbial products through the application of omics and systems-biology tools. Genomic, metagenomic, and metabolomic analyses can guide the selection of compatible, multifunctional strains and illuminate the molecular dialogue between bacteria, plants, and the surrounding microbiome. Coupling these insights with advances in synthetic-community design promises inoculants tailored to specific crops, soils, and stress scenarios. Parallel innovation in formulation—particularly in encapsulation chemistry and controlled-release systems—will be vital to extending shelf-life and ensuring reliable establishment in the field.

Finally, the successful commercialization and adoption of PGPR technologies will depend on addressing regulatory, economic, and educational dimensions. Harmonized quality-control standards, streamlined registration pathways, and robust mechanisms for verifying product viability are needed to build farmer and market confidence. Equally important are efforts to demonstrate clear economic returns and to educate growers on the appropriate use of microbial inputs within integrated management systems. Interdisciplinary collaboration among microbiologists, agronomists, formulation scientists, economists, and policymakers will be indispensable in transforming the considerable scientific promise of PGPR into widespread, durable agricultural impact.

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