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The role of beneficial rhizobacteria in plant growth and soil fertility: A comprehensive review

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Abstract
The rising global demand for food, combined with environmental concerns, requires sustainable agricultural practices. Plant Growth-Promoting Rhizobacteria (PGPR) present a promising alternative to chemical fertilizers and pesticides by boosting plant growth, nutrient uptake, and disease resistance. These beneficial microbes colonize the rhizosphere and enhance crop productivity through various mechanisms such as nitrogen fixation, phosphate solubilization, siderophore production, phytohormone synthesis, and induced systemic resistance. Genera like *Azospirillum, Bacillus, Pseudomonas,* and *Rhizobium* have demonstrated significant benefits across different crops and stress conditions. PGPR also play critical roles in biocontrol and phytoremediation, making them essential components of biofertilizer and biopesticide formulations. Despite their proven potential, field effectiveness is often inconsistent due to environmental variability, strain-host specificity, and formulation challenges. Advances in microbial biotechnology, development of consortia, and regulatory frameworks are vital to improve their performance and adoption. This review emphasizes the mechanisms, applications, and future opportunities of PGPR in transforming modern agriculture into a more resilient and environmentally friendly system.

Keywords: Plant growth-promoting rhizobacteria, *Azospirillum*, biofertilizer, biopesticide and environmentally friendly

Introduction
As the global population is projected to reach nearly 10 billion by 2050 (United Nations, 2015), agricultural systems are facing increasing pressure to sustainably enhance food production. While conventional agricultural intensification strategies can effectively boost crop yields, they often depend heavily on synthetic fertilizers and pesticides. The use of these inputs has contributed significantly to various environmental issues, such as soil degradation, greenhouse gas emissions, and water eutrophication. Therefore, there is an urgent need to explore ecologically responsible alternatives to maintain soil fertility and crop productivity. One promising approach is the use of Plant Growth-Promoting Rhizobacteria (PGPR).
PGPR are a diverse group of beneficial soil bacteria that colonize plant roots and positively influence plant growth and health. They operate through various mechanisms, including nitrogen fixation, phosphate solubilization, siderophore production, the synthesis of phytohormones (such as auxins, cytokinins, and gibberellins), and the suppression of plant pathogens (Kloepper *et al.*, 1988) [26]. These bacteria can be either symbiotic or free-living and are most commonly found in the rhizosphere—the narrow region of soil directly influenced by root secretions and associated microbial activity.
The rhizosphere is a highly dynamic environment that is enriched with exudates, such as amino acids, organic acids, sugars, and secondary metabolites, which influence microbial populations. Beneficial bacteria thrive in this nutrient-rich zone, forming close associations with plant roots and playing critical roles in nutrient cycling, soil structure, and plant health. Genera such as *Azospirillum, Bacillus, Paenibacillus, Pseudomonas, Enterobacter, Klebsiella, Burkholderia, Serratia, Acetobacter, Freauteria, Gluconacetobacter,* and *Herbaspirillum* are well-studied PGPR with potential applications as biofertilizers and biopesticides (Brown, 1974; Glick, 1995) [7].

Since the recognition of *Rhizobium* spp. as a nitrogen-fixing symbiont of legumes in 1886, microbial inoculants have been used in agriculture. However, their application has remained limited in developing countries due to challenges such as formulation stability, accessibility, and performance in the field (Bashan, 1998). Recently, advancements in microbial ecology, genomics, and biotechnology have accelerated the discovery and use of plant growth-promoting rhizobacteria (PGPR) strains that possess multiple beneficial traits for plants (Jain *et al.,* 2021; Aloo *et al*., 2022) [, 1].

In addition to aiding in nutrient mobilization, PGPR also have biocontrol capabilities. Various *Pseudomonads* and *Bacillus* spp. are known to produce antibiotics, siderophores, and lytic enzymes that inhibit plant pathogens and protect crops from soilborne diseases (Weller *et al*., 2002; Kloepper *et al.,* 1989) [52, 27]. Furthermore, PGPR have been shown to induce systemic resistance (ISR) in plants, enhancing their defense responses against a wide range of pathogens (Van Loon, 2007) [48]. Evidence from natural disease-suppressive soils illustrates the protective role of rhizosphere microbiota in agricultural ecosystems (Cook RJ *et al*., 1995) [14].

The potential of Plant Growth-Promoting Rhizobacteria (PGPR) as biofertilizers is receiving increasing global attention, driven by the growing demand for organic food, environmental concerns, and the need to reduce dependence on chemical inputs. Market trends indicate this growing interest, with the global biofertilizer market projected to grow at a compound annual growth rate (CAGR) of over 10%. It is expected to increase from approximately USD 396 million in 2018 to over USD 4.4 billion by 2028. Nonetheless, challenges persist, particularly in areas such as regulatory frameworks, strain specificity, formulation technologies, and achieving consistency in field performance under varying agro-climatic conditions.

To effectively implement PGPR-based technologies, a multidisciplinary approach is necessary, involving agronomists, microbiologists, biotechnologists, and policymakers. The future of this field lies in developing robust, stress-tolerant, and multifunctional microbial consortia designed for specific crops and environmental conditions (Rizvi *et al.*, 2020; Singh *et al.*, 2020). Advanced tools such as multi-omics, synthetic biology, and systems biology are set to enhance our understanding of plant-microbe interactions and enable the creation of next-generation bioformulations with improved shelf life, stability, and efficacy (Kaul *et al.,* 2016; Ding *et al*., 2021).

Benefits of Using Rhizobacteria in Agricultural Crops

Plant Growth-Promoting Rhizobacteria (PGPR) present a promising and eco-friendly alternative to chemical inputs in agriculture, offering numerous benefits to crop growth and resilience. Although there is a relative lack of comparative studies across different crop species and bacterial strains, extensive research has consistently demonstrated the positive effects of PGPR on economically significant crops. These benefits include enhancements in vegetative development, reproductive success, stress tolerance, nutrient acquisition, and disease resistance, supporting the integration of PGPR into sustainable agricultural systems.

1. Enhancement of Vegetative Growth

PGPR significantly improves various vegetative parameters in crops. Inoculation with effective strains has resulted in increased germination rates, root length, biomass, leaf area, chlorophyll content, shoot weight, and essential nutrient uptake, including nitrogen, magnesium, and proteins (Glick *et al*., 1997). Additionally, improvements in hydraulic conductivity, tolerance to abiotic stressors such as drought, and delayed leaf senescence have been observed, all of which contribute to overall plant vigor and resilience.

2. Improvement of Reproductive Traits and Yield

Numerous studies have shown that treatments with Plant Growth-Promoting Rhizobacteria (PGPR) lead to significant enhancements in reproductive parameters, especially grain yield. These growth-promoting effects typically begin during the early developmental stages and continue through harvest, resulting in yield increases of 50% to 70% under certain conditions (Bashan *et al*., 1999; Tran Van *et al*., 2000) [, 45]. The cumulative effects of early stimulation of root and shoot systems contribute to improved panicle formation, flowering, and fruit set.

Disease Suppression and Biocontrol

One of the major advantages of PGPR is their ability to provide systemic resistance against soilborne pathogens, a phenomenon often referred to as "biocontrol." PGPR can suppress a wide range of phytopathogens by producing antibiotics, siderophores, and lytic enzymes, or by outcompeting these pathogens for nutrients and habitats (Glick, 1995). These mechanisms enhance the plant's defence systems and reduce the reliance on chemical fungicides and bactericides.

Abiotic Stress Tolerance

PGPR also help plants tolerate abiotic stresses such as salinity, drought, flooding, high temperatures, and soil acidity. For example, species like *Azospirillum* and *Pseudomonas* have been utilized to alleviate flooding stress (Grichko and Glick, 2001), promote plant growth in acidic soils (Belimov *et al*., 1998a), and diminish the impacts of heat stress (Bensalim *et al.,* 1998). These bacteria assist in stress mitigation through the production of ACC deaminase, regulation of osmolytes, and enhancement of water uptake.

5. Soil Health and Nutrient Cycling

Many plant growth-promoting rhizobacteria (PGPR) strains can solubilize phosphorus, mineralize organic matter, and fix atmospheric nitrogen, thereby enhancing the availability and uptake of nutrients by plants. They also produce phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, which influence root architecture and shoot development. Additionally, through the production of siderophores, PGPR limit iron availability to pathogenic organisms, which indirectly promotes plant growth.

6. Applications in Stressful and Contaminated Environments

In addition to their role in conventional agriculture, PGPR have demonstrated potential in phytoremediation efforts. In soils heavily contaminated with metals, rhizobacteria such as *Bacillus* and *Pseudomonas* species can enhance plant biomass production, facilitating the stabilization and revegetation of toxic environments (Jing *et al.,* 2007) [25]. Their ability to thrive in hostile conditions makes them invaluable for land reclamation and ecosystem restoration.

7. Broad Spectrum Efficacy and Field Performance

Although our understanding of rhizobacterial diversity is still evolving, field and greenhouse studies have shown that certain strains consistently enhance crop growth and productivity, sometimes exceeding control groups by more than 100%. Their reliable performance, whether applied to seeds, roots, or seed pieces, demonstrates the wide applicability of PGPR across different crop systems (Glick, 1995).

Mechanisms of Plant Growth-Promoting Rhizobacteria (PGPR)

1. Phosphate Solubilization

PGPR solubilize inorganic phosphates (such as tricalcium phosphate) using organic acids like gluconic and citric acid, transforming them into forms that are available for plant uptake. (Rodríguez, H., & Fraga, R. 1999) [37]. Ex: *Bacillus megaterium* (Multiplex Durga)

2. Siderophore Production

PGPR produce siderophores that chelate Fe^{3+} in the rhizosphere, depriving pathogens of iron while enhancing plant iron uptake without negatively affecting plant growth. O'Sullivan, D. J., & O'Gara, F. (1992) [34]. Ex: *Bacillus*, *Pseudomonas* (Multiplex Bio Jodi).

3. Biological Nitrogen Fixation (BNF)

Nitrogen-fixing PGPR convert atmospheric nitrogen into ammonia, which enhances soil fertility and reduces the need for synthetic nitrogen fertilizers. Ex: *Rhizobium* (Multiplex Sunrise), *Azospirillum* (Multiplex Algarythum, AZAB), *Acetobacter* (Multiplex Aadhar) Dobbelaere, S., & Okon, Y. (2007) [18].

4. Phytohormone Production

PGPR synthesize plant hormones such as IAA -enhances root architecture, Cytokinins & Gibberellins: stimulate cell division and elongation ex: Multiplex Zee Green, Multiplex Nagamrutha (Spaepen, S., *et al.*, 2007) [44]

5. Antibiosis and Antibiotic Production

PGPR produces antibiotics, including: Phenazines, DAPG, Pyoluteorin, Pyrrolnitrin, and HCN. These compounds inhibit the growth of pathogenic bacteria and fungi in the rhizosphere. Ex: *Pseudomonas* and *Bacillus* sps (Multiplex Sparsha, Biojodi) Weller, D. M. (2007) [51].

6. Enzyme Production Against Pathogens

PGPR secretes enzymes such as chitinases and glucanases that degrade fungal cell walls, helping to suppress diseases like Fusarium root rot. Ex: *Pseudomonas* and *Bacillus* sps (Multiplex Sparsha, Biojodi) Gupta, R., *et al.*, 2006) [22].

7. Competition for Nutrients and Niches

PGPR compete with pathogens for carbon sources and binding sites on root surfaces. Their ability to rapidly colonize through chemotaxis and attachment helps them outcompete soil pathogens (Kloepper, J. W., & Schroth, M. N., 1981) [29] ex: *Pseudomonas* and *Bacillus* sps (Multiplex Sparsha, Biojodi).

8. Induced Systemic Resistance (ISR)

PGPR stimulates the plant immune system by activating pathways involving jasmonic acid, ethylene, and salicylic acid, priming the plant to resist future pathogen attacks. Ex: *Azotobacter, Bacillus, Frateuria* (Multiplex Nalpak) (Van Loon, L. C *et al*.,1998) [48].

9. Rhizosphere Colonization

Effective root colonization (10^6-10^7 CFU/g root) is crucial for the success of PGPR. This depends on microbial traits, root exudates, and environmental compatibility. Ryan, R. P. *et al.*, (2009) [38].

10. Alteration of Rhizosphere Microbiome

PGPR influence the microbial community structure in the rhizosphere by inhibiting pathogens and promoting beneficial symbionts, resulting in a healthier root environment Trivedi, P. *et al.*, 2020 [46].

11. Mineral Solubilization

In addition to phosphorus, PGPR can solubilize other minerals like zinc and potassium, thereby improving the uptake of micronutrients. Ex: Multiplex NALPAK Vassilev, N., *et al.*, 2006 [49].

12. Synergistic Interactions

PGPR often work more effectively in consortia or association with arbuscular mycorrhizal fungi (Multiplex Trishul). These synergistic interactions enhance plant nutrient uptake, stress tolerance, and disease resistance Ex: Multiplex Nalpak Glick, B. R. (1995).

PGPR employs multifaceted strategies, including direct nutrient facilitation and indirect biocontrol, to promote plant health. Their integration into agricultural systems offers sustainable solutions to reduce chemical inputs and enhance productivity.

Factors Affecting the Efficiency of Rhizobacteria (PGPR)

The efficacy of Plant Growth-Promoting Rhizobacteria (PGPR) in promoting plant health and yield is influenced by several biotic and abiotic factors. These include environmental conditions, host specificity, application strategies, and inoculant formulation.

Key factors are discussed below:

1. Soil Moisture Content

Soil moisture plays a critical role in the successful colonization of plant rhizospheres by PGPR after inoculation. Studies have shown that optimal results are obtained when soil moisture is maintained at approximately 40%, as suggested by early work conducted in the Soviet Union (Brown, 1974; Cooper, 1959) [7, 15]. However, excessive moisture may lead to decreased oxygen availability, which can negatively impact aerobic PGPR like *Pseudomonas* spp. (Burr *et al.*, 1978) [8]. The effect of moisture is also strain-specific, necessitating tailored water management based on the PGPR species used.

2. Host Specificity

The effectiveness of PGPR strains is often crop-specific. Certain bacterial strains exhibit high affinity and functionality only with specific plant species, which can limit their general applicability across different cropping systems. Therefore, strain-host compatibility is a key consideration in the development of bioinoculants.

3. Inoculation Density

The initial population of PGPR applied to the plant is critical for ensuring effective colonization and growth promotion. According to Boddey and Dobereiner (1988) [4], a minimum threshold bacterial population must be reached for the inoculant to exert beneficial effects. However, Chanway (1997) [12] observed that excessive bacterial inoculation can negatively impact seed germination and seedling growth, highlighting the need for precise optimization of inoculum load. Effective root colonization (10^6-10^7 CFU/g root) is crucial for the success of PGPR. This depends on microbial traits, root exudates, and environmental compatibility.

4. Temperature Sensitivity

Temperature is another crucial factor affecting PGPR activity. While certain *Pseudomonas* strains are capable of surviving colder climates and even overwintering in soils, others like *Azospirillum* exhibit a preference for warmer conditions, which may limit their effectiveness in temperate regions. This necessitates regional and seasonal selection of PGPR strains based on local climatic conditions.

5. Sterility of Inoculant Carrier Material

The sterility of the carrier material used for bacterial inoculants can significantly influence their performance. Chanway *et al.* (1991) [13] demonstrated that inoculating pine trees with PGPR in sterilized peat-vermiculite carrier material resulted in significantly enhanced plant growth compared to non-sterilized carriers. This highlights the importance of eliminating competing microbes in inoculant formulations to maximize PGPR efficacy.

Table 1: The different Rhizobacteria and their effect on different crops

Rhizobacteria	Plants affected	Effect of Rhizobacteria on different crops	Reference
Azospirillum	Wheat	Increases yield from 15 to 30%	Okon and Labandera-Gonzalez 1994 [32]
	Finger millet	An average of up to 15% yield increase	Rao 1986 [35]
	Sorghum	Leaf senescence delayed, 19-26% Yield increase	Sarig *et al.* 1990 [39]
	Bean	Increased fresh root and shoot weights	Vedder-Weiss *et al.* 1999 [50]
	Maize	Replaces 35-40% of nitrogen fertilizers 15 to 25% yield increase 40% Significant increase in the number of adventitious roots, root length, and root and shoot dry weight. Increased magnesium percentage.	Dobbelaere *et al.* 1999 [17]
	Chickpeas, Faba bean	Significant increases in root nodulation by native rhizobia and improved root and shoot development, an increase in shoot growth, and crop yield	Hamaoui *et al.* 2001 [24]
	Millet	Increased yield up to 30%	Di Ciocco and Rodriguez Caceres 1994 [16]
	Rice	Increased yield by 15-20% in two locations	Omar *et al.* 1989 [33]
	Sunflower	Positive growth responses with respect to germination	Fages and Arsac 1991 [21]
	Mustard	Increased yield of 16 to 128%	Kloepper *et al.* 1989 [27]
Bacillus	Tomato, Pepper	Improves vegetative growth and fruit yield Overcome Transplant vigor Reduction of galling in pepper by root-knot nematode.	Kokalis-Burelle *et al.* 2002 [30]
	Sugar beet	Significant increases in root yield 6.1 to 13.0%, sugar yield 2.3 to 7.8%	Cakmakci *et al.* 2001 [10]
	Sorghum	Increases yield from 15.3 to 33%	Broadbent *et al.* 1977 [6]
	Wheat	Changes in yield of 0 to 114%	Kloepper *et al.* 1989 [27]
	Peanut	Yield increases up to 37%	Turner and Backman 1991 [47]
	Onion	Significant increases in shoot dry weight (12-94%), dry root weight 13-100% and shoot height (12-40%).	Reddy and Rahe 1989 [36]
Burkholderia vietnamiensis TVV75	Rice	Increases of shoot weight (up to 33%), root weight (up to 55%) and leaf surface (up to 30%) observed, with an end grain yield increase of 13-22%.	Tran Van *et al.* 2000 [45]
Pseudomonas spp.	Winter wheat	Biocontrol effects seen against take-all disease caused by *Gaeumannomyces graminis*, 27% yield increase due to inoculation, Controls *Rhizoctonia solani* and *Leptosphaeria maculans*	De Freitas and Germida 1990 [19]
	Potato	Increases of yield from 14-33%, suppresses Soft rot *Erwinia carotovora*	Burr *et al.* 1978 [9]
	Cucumber	Increases fruit numbers by 12% and fruit weight by 18%	
	Maize, Barley Wheat	Increased yield from 15 to 25%	Iswandi *et al.*1987 [23]
	Mung bean	Bacterium promoted nodulation in mung bean, The ethylene production was inhibited in inoculated cuttings	Shaharoona *et al.* 2006 [42]
	Soyabean	Improves early growth	Cattelan *et al.* 1999 [11]
	Maize	Root elongation in maize	Babaloa *et al.* 2003

Beneficial Rhizobacteria and Their Central Role in Biofertilizers

Beneficial rhizobacteria, particularly Plant Growth-Promoting Rhizobacteria (PGPR), have become essential in the development of modern biofertilizers due to their diverse interactions with host plants. These soil dwelling microorganisms colonize the rhizosphere the specific area of soil influenced by root secretions and promote plant growth through various direct and indirect mechanisms. These mechanisms include nitrogen fixation, phytohormone production, phosphate solubilization, and the biological control of plant pathogens (Aloo *et al.*, 2022; Kloepper *et al.*, 1980) [1, 28]. The group of rhizobacteria includes several genera such as *Azospirillum*, *Azotobacter*, *Bacillus*, and *Rhizobium*, as well as endophytic diazotrophs like *Acetobacter* and *Herbaspirillum*, and *Azospirillum*. These microbial taxa form the foundation of biofertilizer formulations, contributing not only to enhanced nutrient availability but also to improved stress tolerance, soil structure, and disease resistance in plants (Boddey & Dobereiner, 1995) [5].

Linking Rhizobacteria to Biofertilizer Applications

Biofertilizers, defined as active microbial inoculants that improve the availability and uptake of essential nutrients in the rhizosphere, are essentially based on beneficial rhizobacterial strains. These strains may act individually or synergistically when formulated into microbial consortia to deliver multiple plant growth-promoting traits. For instance, *Azospirillum* spp. are widely used in biofertilizers due to their associative nitrogen-fixing ability, their capacity to produce indole-3-acetic acid (IAA), and their stimulatory effects on root architecture, which collectively enhance water and nutrient uptake (Okon & Labandera-Gonzalez, 1994) [32].

Similarly, *Azotobacter* and *Bacillus* spp. not only fix atmospheric nitrogen but also solubilize inorganic phosphates, secrete siderophores, and suppress phytopathogens, making them ideal candidates for biofertilizer development (Mishustin & Naumova, 1962) [31].

Recent advances have also highlighted the potential of obligate endophytes such as *Acetobacter diazotrophicus*, *Azospirillum* spp and *Herbaspirillum* spp., which inhabit internal plant tissues and offer stable colonization and continuous nitrogen supply, especially in graminaceous crops like sugarcane and rice (Baldani *et al.*, 1997) [3]. These endophytes, by occupying protected niches within the plant, are less affected by environmental fluctuations, thereby enhancing their reliability in field applications.

Biofertilizer Efficiency and Rhizobacterial Synergy

The efficiency of biofertilizers is inherently linked to the biology of rhizobacteria factors such as strain specificity, inoculum density, formulation quality, and environmental compatibility all affect performance outcomes. For example, optimal plant responses have been observed when inocula contain around 10^7 cfu/seed of *Azospirillum*, with deviations leading to suboptimal germination or phytotoxic effects (Okon *et al*., 1994; Chanway, 1997). [32, 12] Furthermore, sterilized carrier materials significantly improve inoculant efficacy, likely by reducing competition from native microflora (Chanway *et al.*, 1991) [13].

The growing body of research also supports the development of microbial consortia as next generation biofertilizers, where rhizobacterial strains are combined to express complementary traits such as nitrogen fixation, phosphorus solubilization, and pathogen suppression, offering a more holistic solution for sustainable agriculture Example Multiplex Nalpak and Organic magik (Singh *et al*., 2020). Such formulations not only enhance yield but also improve soil health, reduce chemical input dependency, and contribute to environmental conservation.

Rhizobacteria as Biopesticides

Plant Growth-Promoting Rhizobacteria (PGPR) have long been recognized for their ability to enhance crop productivity through nutrient acquisition and hormone production. However, recent research increasingly highlights their biopesticidal potential, adding another dimension to their utility in sustainable agriculture. These beneficial rhizobacteria play a dual role in stimulating plant growth and offering protection against a wide range of phytopathogens through both direct antagonistic mechanisms and indirect systemic responses.

Among these, species of *Pseudomonas* and *Bacillus* have emerged as potent biocontrol agents. Inoculation with *Pseudomonas*, *Bacillus*, and *Mycobacterium spp* significantly enhanced root and shoot growth in cotton and pea. These PGPR strains not only improved plant biomass and nutrient uptake (N, P, K) but also exhibited antagonistic activity against pathogenic fungi while producing phytohormones like auxin and showing nitrogenase activity (Egamberdiyeva & Höflich, 2004) [20].

The ability of PGPR to improve plant micronutrient status has also been demonstrated. For example, treatments with *Pseudomonas putida* (Multiplex Bio Jodi) and other isolates nearly doubled the iron content in rice grains, suggesting that PGPR applications can address nutritional deficiencies in crops and in human diets. These rhizobacteria facilitate enhanced iron translocation from roots to shoots and increase grain bioavailability, supporting both plant health and food quality.

The overwintering capability of *Pseudomonas* spp., their possession of ACC deaminase genes (Hall *et al.*, 1996), and their ability to degrade plant stress ethylene levels under drought and flooding conditions provide plants with a buffer against abiotic stressors. Moreover, *Pseudomonas fluorescens* and *P. putida* strains exert a competitive advantage in the rhizosphere through the production of siderophores, depriving native microflora of iron and thereby suppressing soil-borne pathogens (Schroth & Hancock, 1982) [40].

Wild-type *Pseudomonas* strains that produce antibiotics significantly increased potato plant weight by 300-500%, while mutants lacking these antibiotic traits failed to do so, despite similar colonization abilities. This clearly illustrates that antibiosis and microbial competition are key contributors to PGPR-mediated plant growth and disease suppression (Kloepper *et al*., 1989) [27].

Additionally, PGPR can alter rhizosphere microbial populations by suppressing fungal pathogens and gram-positive bacteria, converting disease-conducive soils into suppressive ones. For example, the pseudofactin-producing *Pseudomonas* strain B10 was shown to improve soil suppressiveness by limiting pathogen access to iron via siderophores (Kloepper *et al*., 1980) [28].

Other mechanisms by which PGPR act as biopesticides include:

- Production of glycolipids that damage pathogenic zoospores (e.g., *Pythium* spp.)
- Degradation of fusaric acid (a *Fusarium* toxin) by *Burkholderia* spp.
- Interference with pathogenicity by inhibiting enzyme systems like pectinases
- Synergy with soil amendments like Zn^{2+}, chitin, and chitosan, which boost microbial efficacy and alter rhizosphere chemistry (Schouten *et al*., 2004) [41]

The structural adaptation of *Pseudomonas* spp. for effective root colonization such as chemotaxis, biofilm formation, and microcolony development, supports their long-term survival and competitive advantage in the rhizosphere (Hallmann *et al.*, 1999). Furthermore, their root-colonization success depends on their ability to metabolize root exudates like malate and succinate rather than simple sugars.

Importantly, biopesticide PGPR are also economically and environmentally advantageous. For example, *Pseudomonas*-based inoculants used alongside 75% of the recommended NPK dosage resulted in 15-22% yield increases, comparable to full NPK application, thereby offering a sustainable alternative to chemical pesticides and fertilizers (Shaharoona *et al*., 2008) [43].

Conclusion

Plant Growth-Promoting Rhizobacteria (PGPR) play a pivotal role in sustainable agriculture by functioning as both biofertilizers and biopesticides. They enhance nutrient uptake, fix atmospheric nitrogen, stimulate root growth, and suppress plant diseases, reducing the need for chemical fertilizers and pesticides.

Beneficial genera such as *Azospirillum*, *Rhizobium*, *Pseudomonas*, and *Bacillus* contribute to improved crop yields and soil health. PGPR-based inoculants have also shown promise in improving plant stress tolerance and micronutrient content, such as iron in rice grains.
However, their field performance remains inconsistent due to formulation challenges, environmental variability, and lack of quality control. Effective delivery systems, carrier selection, and strain compatibility are crucial for their success.
With growing global interest in eco-friendly farming, advancing PGPR technologies through better formulations, microbial consortia, and regulatory support can significantly contribute to food security and environmental sustainability

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