International Journal of *Plant Biology*

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Review

Plant-Growth-Promoting Microorganisms: Their Impact on Crop Quality and Yield, with a Focus on Rice

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Abstract: This article presents a systematic review of the ecophysiological mechanisms underpinning the essential role of plant-growth-promoting microorganisms (PGPMs) in improving rice yield and quality. The scientific literature is thoroughly reviewed, highlighting how PGPMs positively influence the growth, development, and health of rice plants. Key aspects, such as nitrogen fixation, nutrient solubilization, hormone production, and disease resistance induction, are emphasized. Additionally, technological advancements related to PGPM use are analyzed, including the identification of effective strains, the formulation of enhanced biofertilizers, and genetic engineering. The article concludes that PGPMs represent a promising tool with which to boost the sustainability and productivity of rice cultivation, providing a robust foundation for future research and practical applications in a field crucial to global food security.

Keywords: plant-growth-promoting microorganisms; rice quality; rice yield; ecophysiological mechanisms in rice; biofertilizers; rhizobacteria; sustainable agricultural production

Academic Editor: Naser A. Anjum

Received: 28 November 2024
Revised: 28 December 2024
Accepted: 5 January 2025
Published: 9 January 2025

Citation: Ríos-Ruiz, W.F.; Jave-Concepción, H.G.; Torres-Chávez, E.E.; Rios-Reategui, F.; Padilla-Santa-Cruz, E.; Guevara-Pinedo, N.E. Plant-Growth-Promoting Microorganisms: Their Impact on Crop Quality and Yield, with a Focus on Rice. *Int. J. Plant Biol.* **2025**, *16*, 9. https://doi.org/10.3390/ijpb16010009

1. Introduction

Rice (*Oryza sativa* L.) is one of the most globally significant crops, serving as the staple food for more than half of the world's population. Its importance lies not only in its role in food security but also in the economy of many countries, particularly in Asia, which accounts for 90% of global production and consumption [1–3]. Additionally, rice holds profound cultural significance in various communities [4]. The growing global demand, driven by population growth and rising incomes, underscores the need to sustainably increase its production.

Rice production faces numerous challenges that impact both yield and quality. Key issues include declining soil fertility [5,6], depletion of water resources [7], the emergence of pests and diseases [8], and the effects of climate change [9]. These factors not only limit the yields but also compromise the grain quality [10,11]. Furthermore, intensive agriculture and excessive use of chemical fertilizers have caused soil degradation and environmental problems, such as water pollution [12] and greenhouse gas emissions [13,14]. In this context, achieving sustainable production that maintains high yields without sacrificing rice quality is crucial.

Plant-growth-promoting microorganisms (PGPMs) have emerged as a promising solution to address these challenges. These microorganisms, including bacteria and fungi that colonize plant roots, promote growth through various mechanisms. They enhance nutrient availability [15–17], stimulate root development [18], increase tolerance to biotic and abiotic stress [19], and contribute to agricultural ecosystem sustainability [20,21]. Consequently, PGPMs not only improve the yield of rice, but also its nutritional quality. A promising strategy in this context is biofortification, which increases essential nutrient levels in rice grains while reducing the dependency on chemical inputs [22,23]. These advancements support the development of more sustainable and environmentally friendly agriculture.

This article provides a systematic review of the role of PGPMs in improving rice yield and quality, with a particular focus on the ecophysiological mechanisms involved. The main types of PGPMs, their mechanisms of action, and their impact on grain nutritional quality and crop yield are identified and analyzed. Agronomic and environmental considerations for their application in rice cultivation, as well as the challenges and future perspectives of their research and use, are also discussed. This review aims to serve as a reference for future agricultural research and practices, promoting more efficient and sustainable rice production.

2. Materials and Methods

The literature reviewed in this study was gathered using various scientific platforms, such as Web of Science, Scopus, Science Direct, and Google Scholar. Key terms used included "Plant-Growth-Promoting Microorganisms", "PGPM", "Rice Quality", "Rice Yield", "Ecophysiological Mechanisms in Rice", "Biofertilizers", "Rhizobacteria", and "Sustainable Agricultural Production." The selected studies comprise peer-reviewed experimental research, ensuring the quality and relevance of the data considered in this review.

3. Plant-Growth-Promoting Microorganisms (PGPM)

PGPMs are essential for sustainable agriculture, representing an eco-friendly alternative to conventional chemical inputs. Their ability to enhance nutrient availability, protect plants against pathogens, and increase tolerance to environmental stress makes them vital allies in optimizing the yield and quality of crops such as rice. Their diversity and functionality provide a strong foundation for their study and application in modern agriculture.

3.1. Definition and Classification of PGPMs

PGPMs include a diverse group of bacteria and fungi that interact with plant roots, promoting growth and development through biological and biochemical mechanisms. Key processes include enhancing nutrient availability, producing phytohormones, protecting against pathogens, and inducing resistance to abiotic and biotic stress [24,25]. These microorganisms can occur naturally in the soil or be applied as specific inoculants, providing a sustainable alternative to chemical fertilizers and pesticides. Their use benefits soil health and crop productivity, improving the resilience of rice plants under climate change conditions [26].

According to Kumar et al. [27], PGPMs are classified based on their type, function, and mechanism of action. Within plant-growth-promoting bacteria, two main categories are distinguished: plant-growth-promoting rhizobacteria and endophytic bacteria. Among plant-growth-promoting fungi, arbuscular mycorrhizal fungi and rhizospheric fungi are the most notable. Additionally, other significant groups include actinobacteria and cyanobacteria, which also play a crucial role in promoting plant growth, as described in Table 1.

Table 1. Type of plant-growth-promoting microorganism (PGPMs), characteristics, mechanisms of action, and references.

Type of PGPM	Characteristics	Mechanisms of Action	References
		Rhizobacteria	
Azospirillum spp.	Diazotrophic bacteria that fix atmospheric nitrogen.	Nitrogen fixation. Production of phytohormones. Promotion of root growth. Proteins involved in the biosynthetic pathway of flavonoids, defense, hormonal signaling pathways, and nitrate and sugar transport.	[28,29]
Azotobacter spp.	Diazotrophic bacteria that fix atmospheric nitrogen.	Nitrogen fixation. Production of phytohormones. Promotion of root growth.	[28]
Pseudomonas spp.	Versatile bacteria known for their biocontrol and growth-promoting capabilities.	Production of siderophores. Production of antibiotics and lytic enzymes. Phosphorus solubilization. Zinc and potassium solubilization.	[30–32]
Bacillus spp.	Spore-forming bacteria that improve soil and plant health.	Phosphorus and potassium solubilization. Production of antibiotics. Induction of systemic resistance.	[16,33–38]
		Endophytic bacteria	
Herbaspirillum spp.	Diazotrophic bacteria.	Nitrogen fixation. Production of phytohormones. Promotion of root and aerial growth.	[29,39–41]
Enterobacter spp.	Ubiquitous bacteria that promote growth within the plant.	Salinity stress relief, production of indole-3-acetic acid, siderophores, and phosphate solubilization. Increase in rice growth parameters.	[31,42]
		Plant-Growth-Promoting Fungi	
Arbuscular mycorrhizal fungi (AMF).	They form symbiotic associations with plant roots.	Improvement in phosphorus and other nutrient absorption. Increase in drought and salinity stress tolerance. Improvement in soil structure.	[43–47]
Trichoderma spp.	Biocontrol fungi that also promote plant growth.	Production of enzymes that degrade pathogens. Induction of systemic resistance in plants. Nutrient solubilization.	[48]
		Actinobacteria	
Streptomyces spp.	Filamentous bacteria known for producing natural antibiotics.	Production of antimicrobial compounds. Phosphorus solubilization. Promotion of root growth.	[49]
Micromonospora spp.	They improve the availability of nutrients.	Production of enzymes that degrade organic matter. Improvement in soil structure and plant health.	[50,51]

Table 1. *Cont.*

Type of PGPM	Characteristics	Mechanisms of Action	References
		Cyanobacteria	
Anabaena spp.	Photosynthetic bacteria that fix nitrogen and live in symbiosis with certain plants.	Atmospheric nitrogen fixation. Improvement in soil structure through the production of mucilage. Increase in soil fertility.	[52,53]
Nostoc spp.	Cyanobacteria that form symbiosis with aquatic and terrestrial plants.	Nitrogen fixation. Production of bio stimulants that promote rice growth, especially in saline environments.	[54,55]

3.2. Main PGPMs Used in Rice Crops

In modern agriculture—particularly in rice cultivation—plant-growth-promoting microorganisms (PGPMs) play a fundamental role in improving soil health and increasing productivity. Among the most commonly used PGPMs are decomposer consortia and biocontrol agents, such as *Streptomyces* sp., *Cytophaga* sp., *Bacillus* sp., *Pseudomonas* sp., and *Trichoderma* sp.; biofertilizers, such as *Azotobacter* sp., *Azospirillum* sp., *Pseudomonas* sp., *Bacillus* sp., *Acinetobacter* sp. [56], and *Bacillus pumilus* JPVS11 [57]; and other microorganisms that enhance crop yield, such as *Bacillus cereus* MKGB, *Pseudomonas fluorescens* MKGPf, and *Azospirillum oryzae* MKGAz [58]. These PGPMs offer multiple benefits, including improved nutrient uptake (*Pantoea ananatis*, *Enterobacter* sp., and *Piriformospora indica*) [59], protection against pathogens (*Bacillus* sp., *Pseudomonas* sp., and *Streptomyces* sp.) [60], induction of systemic resistance (*Pseudomonas fluorescens* and *Bacillus velezensis* LS123N) [61,62], and enhancement of soil structure (*Paenibacillus* sp., *Rhizobium* sp., *Bacillus* sp., *Azotobacter* sp., *Pseudomonas* sp., *Glomus* sp., and *Gigaspora albida*) [6]. The strategic selection and application of these PGPMs can significantly increase both the yield and quality of rice, fostering more sustainable and efficient agriculture. Notable examples include *Citrobacter bitternis* p9a3m, *Burkholderia ubonensis* la3c3, *Burkholderia vietnamiensis* la1a4, *Bacillus siamensis* TUR07-02b, and *Priestia megaterium* SMBH14-02 [15,16].

4. Ecophysiological Mechanisms of PGPMs in Rice

4.1. Nitrogen Fixation: Diazotrophic Bacteria and Their Role in Biological Nitrogen Fixation

Biological nitrogen fixation (BNF) is a crucial process through which certain diazotrophic microorganisms convert atmospheric nitrogen (N_2) into forms available to plants, such as ammonium (NH_4^+). This process is essential for soil fertility and agricultural productivity, particularly in crops such as rice, which have high nitrogen demands [28,63]. Diazotrophic bacteria play a fundamental role in this process, providing a sustainable source of nitrogen, improving soil health, and reducing dependence on chemical fertilizers. Research and application of these bacteria in modern agriculture is a significant step toward more eco-friendly and efficient agricultural practices.

Diazotrophic bacteria can be free-living [64,65], can be associated with the rhizosphere [16], or can be endophytic [66]. Among the most studied in the context of rice cultivation are *Azospirillum* spp., known for promoting plant growth through nitrogen fixation and the production of phytohormones [28]; Rhizobia, which are typically known for forming nodules in legumes, can also establish associations with non-leguminous plants [67]; and *Herbaspirillum* spp. and *Burkholderia* spp., endophytic bacteria that colonize the internal tissues of rice, contributing to nitrogen nutrition and plant growth [39].

The nitrogen fixation process is mediated by the enzyme nitrogenase, which converts N_2 into NH_4^+ under anaerobic conditions, as nitrogenase is highly sensitive to oxygen. Diazotrophic bacteria employ several strategies to protect this enzyme from oxygen, such as creating anaerobic microenvironments and rapid oxygen respiration [68]. The basic reaction of nitrogen fixation is $N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16Pi$ [69].

The resulting ammonium is released into the soil or absorbed directly by plants, which assimilate it and incorporate it into amino acids and other essential biomolecules [70]. This process enriches the soil with available nitrogen, improving its fertility and reducing the need for chemical fertilizers [71]. The availability of fixed nitrogen increases rice growth and yield [15,16]. Additionally, some diazotrophic bacteria produce phytohormones, such as indole acetic acid, which stimulate root and vegetative development [72]. The use of diazotrophic bacteria helps reduce the environmental impact of chemical fertilizers, improving soil health and reducing pollution [65].

Despite decades of research, there is still no solid evidence that the inoculation of non-leguminous crops with diazotrophic bacteria consistently leads to significant atmospheric nitrogen (N_2) fixation, and many products make unsubstantiated claims regarding their effectiveness. Thus, there is a pressing need for regulation to ensure that inoculant products provide independent and verifiable evidence of their capacity to fix atmospheric N_2, protect nitrogenases, remain active throughout the crop cycle, and demonstrate measurable effects under field conditions [73].

Finally, diazotrophic bacteria can improve rice resistance to abiotic stress conditions, such as salinity and drought, by modulating stress responses and enhancing water use efficiency [74,75]. Figure 1 illustrates the mechanisms of biological nitrogen fixation in rice cultivation, highlighting the role of diazotrophic bacteria.

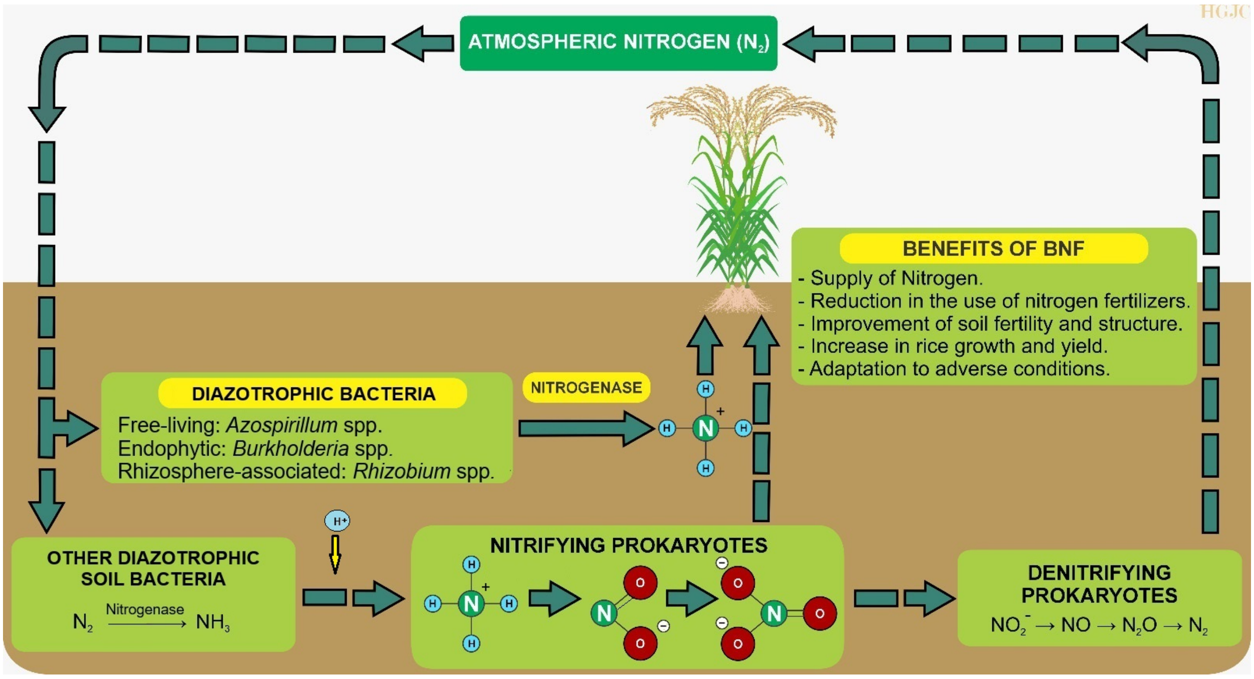

Figure 1. Biological nitrogen fixation (BNF) in rice cultivation. The diagram illustrates the mechanisms of BNF in rice cultivation, highlighting the role of diazotrophic bacteria. These bacteria can live freely, associate with the rhizosphere, or be endophytic. The nitrogen fixation process is depicted, showing how the enzyme nitrogenase catalyzes the conversion of atmospheric nitrogen (N_2) into ammonium (NH_4^+), which is then absorbed by the rice plant. The diagram also emphasizes the role of nitrogen-fixing bacteria in enriching the soil fertility, reducing the need for chemical fertilizers and enhancing plant growth through the production of phytohormones.

4.2. Phosphate Solubilization: Mechanisms of Solubilization and Phosphorus Availability for Plants

Phosphorus (P) is an essential nutrient for plants, playing a crucial role in photosynthesis, energy transfer, and nucleic acid synthesis [76,77]. However, in many soils, phosphorus is present in insoluble forms that plants cannot easily absorb [78,79]. PGPMs, particularly certain bacteria and fungi, are fundamental in phosphate solubilization, increasing phosphorus availability for plants and improving their growth and productivity.

The phosphate solubilization process by PGPMs includes several mechanisms, such as the production of organic acids, phosphatase enzymes, and siderophores, demonstrating the multifunctionality of these microorganisms [80]. The organic acids produced by PGPMs acidify the rhizosphere, lowering soil pH and dissolving insoluble inorganic phosphates, such as calcium, iron, and aluminum phosphates, thereby releasing soluble phosphate ions that plants can absorb [81]. Phosphatase enzymes hydrolyze organic phosphate compounds, releasing the inorganic phosphate available for plants [82,83]. Additionally, siderophores chelate iron from the environment, releasing the phosphate that had been bound to iron compounds, further increasing the availability of this nutrient [84,85].

Another interesting mechanism is used by some chemolithotrophic PGPMs, which oxidize mineral compounds, releasing phosphate in the process. A notable example is *Bacillus subtilis*, which releases organic acids that enable the solubilization of fluorapatite, the main component of rock phosphate ($Ca_5(PO_4)_3F$) [86,87]. This process not only improves phosphorus availability but also facilitates the absorption of other essential nutrients, enhancing the efficiency of photosynthesis and biomolecule synthesis.

To prevent the failure of biofertilizer use, it is essential to investigate the appropriate amounts of inoculants for different plant and soil conditions, as well as the various microbial interactions between the applied PGPR and other soil inhabitants, prior to their application [88].

The ultimate result of these mechanisms is increased crop yield and quality, better resistance to diseases and abiotic stress, and a reduction in the need for chemical phosphate fertilizers, contributing to the sustainability of agricultural systems and improved soil health [89,90]. Figure 2 illustrates the processes involved in phosphate solubilization in rice cultivation.

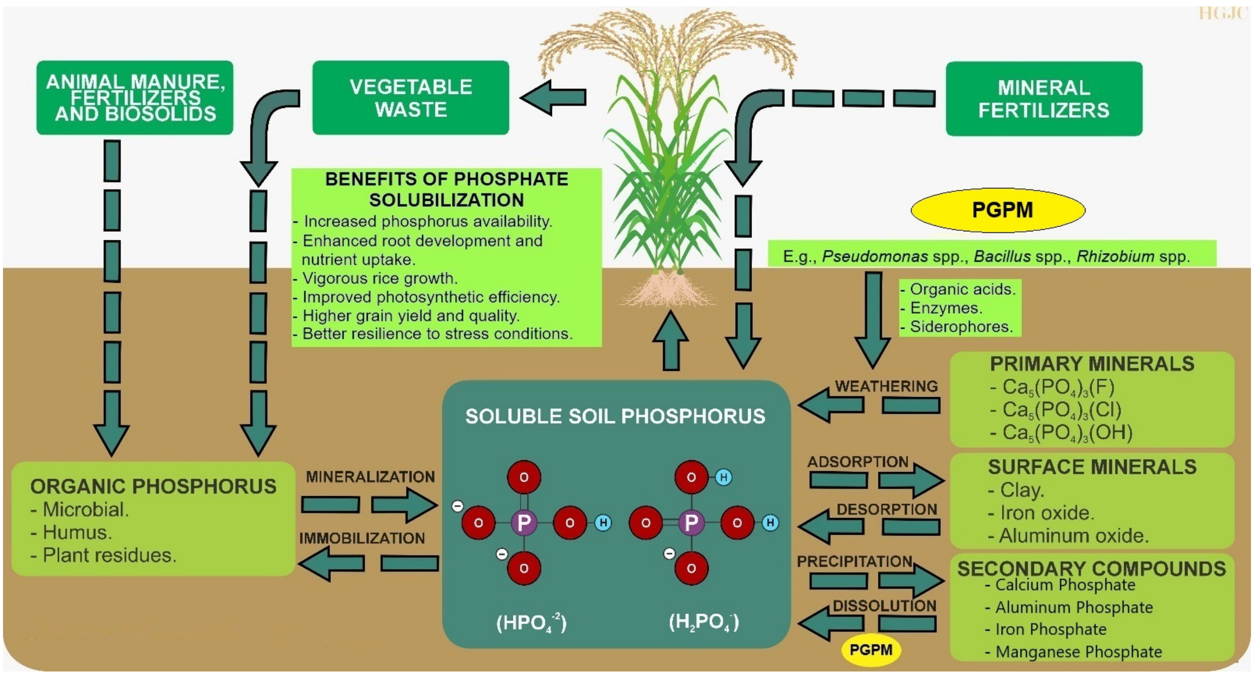

Figure 2. Phosphate solubilization in rice cultivation. The diagram illustrates how bacteria and fungi produce organic acids, phosphatase enzymes, and siderophores to solubilize phosphates, releasing

soluble phosphate ions that plants can absorb. The diagram highlights the benefits of increased phosphorus availability, improved plant growth, reduced use of chemical fertilizers, and enhanced resistance to abiotic stress. PGPM = plant-growth-promoting microorganism.

4.3. Solubilization of Other Elements Such as Potassium, Zinc, and Iron

In addition to phosphorus, other essential elements such as potassium (K), zinc (Zn), and iron (Fe) are crucial for plant growth and development [81–93]. However, in many soils, these are present in insoluble forms that plants cannot absorb [94–96]. PGPMs play a crucial role in the solubilization of these elements, improving their availability and promoting balanced plant nutrition [97–99]. The solubilization of potassium, zinc, and iron by PGPMs is an essential process that enhances the availability of these nutrients for plants, demonstrating the multifunctionality of these microorganisms [100–102].

PGPMs produce organic acids such as citric, malic, and oxalic acids, which act on insoluble potassium minerals, releasing potassium ions (K^+) available for plants. Additionally, certain bacteria synthesize enzymes that degrade potassium minerals, thus increasing the soluble fraction of this element [96]. Similarly, the secreted organic acids and the production of siderophores by these microorganisms have the ability to chelate zinc and iron, improving their availability for plants [103]. This solubilization process contributes to a more efficient nutrition and increased tolerance to abiotic stress in plants, reflected in significant increases in crop yield and quality. Furthermore, the use of PGPMs reduces the dependence on chemical fertilizers, favoring environmental sustainability and the long-term conservation of soil health.

4.4. Production of Phytohormones: Auxins, Gibberellins, Cytokinins, and Their Impact on Plant Growth

Phytohormones are organic compounds produced in small amounts by both plants and certain microorganisms, and they play a crucial role in regulating and coordinating plant growth and development. Among the most important phytohormones are auxins, gibberellins, and cytokinins [104,105].

4.4.1. Auxins

Auxins, essential compounds for plant growth, are synthesized by various microorganisms, including *Azospirillum* spp., *Pseudomonas* spp., and *Bacillus* spp. [16,106–111]. These plant hormones are produced through the tryptophan biosynthesis pathway, converting them into indole-3-acetic acid (IAA), the most common auxin [112]. Their role is crucial in plant development, particularly in promoting root growth. Auxins stimulate the elongation and branching of roots, thereby improving water and nutrient absorption, strengthening the plant, and increasing its ability to resist stress [113]. Additionally, they regulate the growth and formation of organs such as leaves and flowers, promoting a balanced and healthy development of the plant [114]. In situations of abiotic stress, auxins can be key to plant adaptation, improving their tolerance to drought, salinity, and extreme temperatures [115].

4.4.2. Gibberellins

Gibberellins, key plant hormones in the growth and development of plants, are synthesized by various microorganisms, including *Gibberella fujikuroi*, *Rhizobium* spp., and *Azospirillum* spp. [116]. These diterpene compounds are produced through the mevalonic acid pathway [117]. Their main function is to stimulate stem elongation, resulting in increased plant height and better exposure to sunlight [118,119]. Additionally, gibberellins play a crucial role in seed germination by breaking dormancy and promoting germination, ensuring faster and more uniform germination, which is vital for crop establishment [120].

Furthermore, these hormones influence fruit development and growth, improving both their size and quality, which significantly increases crop yield [121].

4.4.3. Cytokinins

Cytokinins, plant hormones essential for the growth and development of plants, are synthesized by various microorganisms, such as *Rhizobium* spp., *Pseudomonas* spp., and *Azotobacter* spp. [122,123]. These compounds, known as modified adenines, such as zeatin, are produced from the precursor adenosine monophosphate (AMP) [124]. Their main function is to stimulate cell division in roots and shoots, increasing the production of new tissues and promoting more vigorous growth [125]. Furthermore, cytokinins play a crucial role in delaying the leaf senescence process, thereby extending their lifespan and enhancing photosynthesis and plant yield [126,127]. These hormones also interact with auxins to regulate shoot and root formation, maintaining a balance between root and aerial growth and ensuring the overall development of the plant [114].

The synergy between auxins, gibberellins, and cytokinins offers significant improvements in the structure and functionality of the root system, favoring more efficient nutrient and water absorption, which are essential for plant growth and productivity. This hormonal interaction promotes robust and accelerated growth, resulting in a notable increase in crop yield and an improvement in the quality of agricultural products [128]. Furthermore, the phytohormones synthesized by PGPMs contribute to the adaptability and resistance of plants to adverse conditions, strengthening their ability to withstand both abiotic and biotic stress, ensuring more stable and reliable production [129].

4.5. Production of Siderophores

Siderophores are low molecular weight organic compounds with a high affinity for ferric ions (Fe^{3+}), produced by various microorganisms such as bacteria and fungi, in response to iron limitations in their environment [130]. This mechanism is essential for acquiring iron, a key element for both microorganisms and plants. The production of siderophores enhances the availability of iron in the soil and rhizosphere, promoting plant nutrition and increasing resistance to pathogens and abiotic stress [131,132]. Furthermore, their application in agriculture, through PGPMs, has shown significant improvements in plant growth in saline soils with iron limitations [133].

The biosynthesis of siderophores uses precursors such as amino acids and carboxylic acids [134]. Among the most common siderophores are hydroxamates, catecholates, and carboxylates, depending on the producing microorganism [135]. Microorganisms detect iron levels in their environment and, through regulators such as Fur in *Escherichia coli*, activate siderophore synthesis under iron deficiency conditions [136]. Siderophores chelate available iron, and the siderophore–iron complexes are transported into microbial cells through specific transport systems, as in *Pseudomonas* spp., where pyoverdine is introduced via membrane proteins [137,138]. This process not only optimizes photosynthesis and other fundamental metabolic processes but also significantly enhances root development, improving the uptake of nutrients and water by plants [99]. Additionally, plants deploy various immune defenses in response to microbial interactions, including ferroptosis, a type of iron-regulated cell death. In this context, *Streptomyces hygroscopicus* OsiSh-2 plays a crucial role in improving rice disease resistance through the production of the siderophores that regulate ferroptosis. This mechanism effectively balances mutualistic symbiosis and host defense, highlighting its potential to enhance crop productivity and resilience [139].

By competing with pathogens for iron, siderophores also reduce the availability of this iron for these pathogens, limiting plant diseases [25]. Notable examples of siderophore producers include *Pseudomonas* spp. (pyoverdine and pyochelin), *Bacillus* spp. (bacillibactin and petrobactin), and *Rhizobium* spp. (rhizobactin), which play key roles in iron nutrition and pathogen protection, as well as enhancing processes such as nodulation and nitrogen fixation in legumes [131,132,140,141].

4.6. Biocontrol of Pathogens

The biocontrol of pathogens by PGPMs is a key process that uses competition mechanisms and the production of antimicrobial substances to inhibit the growth and spread of pathogens, thereby improving agricultural sustainability and productivity [142–145]. PGPMs compete with pathogens for essential resources such as iron and nitrogen, sequestering nutrients through the production of siderophores and colonizing the same ecological niches, which limits the pathogens' ability to establish themselves and cause diseases [3]. Additionally, PGPMs release antimicrobial substances and enzymes that degrade the cellular components of pathogens. Examples of PGPMs include *Trichoderma* spp., which produces antifungal enzymes; *Pseudomonas* spp., which produces bacteriocins and siderophores; and *Bacillus* spp., which produces antimicrobial peptides and degrading enzymes [35,146,147]. The application of these PGPMs in integrated pest management strategies reduces the use of chemical pesticides, strengthens plant resistance, and promotes sustainable agricultural practices, improving plant health and reducing the risk of diseases [148–150].

4.7. Abiotic Stress Tolerance: Resistance to Drought, Salinity, and Other Adverse Conditions

Abiotic stress tolerance is crucial for plant survival and growth in adverse environments, and beneficial PGPMs play a key role in this enhancement through various mechanisms, such as the modulation of plant hormones, promotion of nutrient uptake, production of exopolysaccharides that retain moisture, induction of phytohormones such as abscisic acid to conserve water, production of metabolites and antioxidant enzymes to protect against oxidative stress, and nutrient solubilization in saline soils [151–153]. These microorganisms also improve soil microbiota diversity and activity, activate defense gene expression, and strengthen plants' internal mechanisms, thus increasing their resistance to drought, salinity, and other adverse conditions [154–156]. The strategic application of PGPMs in agriculture enhances crop productivity in regions affected by challenging conditions, reduces the reliance on water and fertilizers, and promotes more sustainable agriculture with a lower environmental impact [157–159].

As previously described, microorganisms can promote plant growth and mitigate abiotic and biotic stresses; however, Weinand et al. [23] have reported contrasting results when evaluating three *Bacillus* isolates in rice. Two isolates of *B. pumilus* inhibited fungal growth and reduced the incidence of brown spot in certain varieties but lacked classic growth-promoting traits. On the other hand, *B. megaterium* exhibited the ability to produce auxins, although it failed to suppress the disease. These findings demonstrate that bacteria can benefit plants without possessing traditional growth-promoting traits. Moreover, although the efficacy of numerous species has been shown, a significant gap remains between understanding their mechanisms of action and their practical application as biofertilizers [160].

5. Genetic Engineering of PGPMs of Importance for Rice Cultivation

Genetic engineering applied to PGPMs in rice cultivation aims to optimize their capabilities to maximize the benefits provided to the plants. These strategies include the insertion of nif genes into non-diazotrophic bacteria to confer nitrogen fixation capabilities, expanding their functionality in agricultural soils [161,162]. On the other hand, transcriptome analyses in diazotrophic bacteria such as *Burkholderia vietnamiensis* [163] and the study of the phenogenetic profile of *Azospirillum* [164] have led to significant advances in understanding the molecular mechanisms associated with nitrogen fixation.

These studies have contributed to the development of strategies to reduce dependency on chemical fertilizers by optimizing biological nitrogen fixation. Additionally, potassium- and phosphorus-solubilizing microorganisms are essential in modern biofertilizers, the functionality of which has been enhanced through advanced biotechnology. For instance, genetic engineering has enabled the creation of genetically modified microorganisms that increase biofertilizer efficiency [165].

Moreover, the incorporation of genes producing antimicrobial compounds in bacteria such as *Bacillus* and *Pseudomonas* increases their ability to combat soil pathogens [166–179]. Furthermore, genetic modification of bacteria to express genes that help plants tolerate stress conditions such as drought or salinity has improved crop resilience [170,171].

Genetic engineering also allows for the development of more effective microbial consortia through the synergistic interaction between modified PGPMs, such as the inoculation of designed photosynthetic diazotrophs [172]. Finally, the use of tools such as CRISPR Cas9 has revolutionized precise microbial genome editing, enabling efficient and controlled improvements in specific PGPM functions [173,174].

6. Impact of PGPMs on Rice Quality

The improvement of the nutritional content of crops is essential to address nutrient deficiencies in the human diet and improve public health, and PGPMs play a key role in this process [110,175]. By interacting with plants, PGPMs modify their metabolism to increase the accumulation of proteins, vitamins, and essential minerals, thereby improving the nutritional quality of crops [176,177]. Through biological nitrogen fixation and amino acid production, PGPMs enhance the nutritional content of plants [15,16,178], promoting more sustainable agricultural production with a lower environmental impact [179].

On the other hand, the presence of contaminants and toxins in food represents a risk to public health and the environment. PGPMs can reduce these risks through bioremediation, degradation, and detoxification processes [180,181]. Examples of PGPMs include *Pseudomonas putida* and *P. aeruginosa*, which degrade hydrocarbons and pesticides [182,183], respectively, and *Bacillus* spp., which produce enzymes that break down mycotoxins [184,185].

7. Impact of PGPMs on Rice Yield

Increases in biomass and grain yield are crucial to meet the growing global food demand, and PGPMs play a key role in this process by interacting with plants and soil, promoting plant growth, improving nutrient absorption, and enhancing resistance to both biotic and abiotic stress factors [6]. They also modulate the expression of genes involved in photosynthesis and synthesize growth compounds that promote cell division and elongation of plant tissues [186,187].

The inoculation of plants with growth-promoting bacteria is an established technology for rhizobia and an emerging one for other bacteria, the success of which depends on the efficacy of the bacterial isolate and the application technology [188]. Microbial inoculants have sustainably improved agricultural yields but face challenges such as those associated with expanding their use to more crops, adapting to diverse agroecological conditions, and mitigating environmental stresses [189]. While rhizobia have demonstrated consistent success, other inoculants have shown variable results, highlighting the importance of understanding their ecology and modes of action, as well as rigorously validating their field efficacy [190]. Advances in omics and next-generation sequencing technologies have enabled the development of biofertilizers based on microbial consortia, which are more resilient and effective than traditional ones. However, their implementation faces barriers such as the diversity of the plant microbiome, the need to design specific inoculants, and the interactions between abiotic and biotic factors, in addition to requiring new production technologies and studies on their environmental impact [191]. A collaborative approach between researchers and farmers, integrating advanced technologies such as amplicon sequencing, machine learning, and synthetic biology, is essential to optimize the development and use of microbial inoculants, thus enhancing their performance across diverse agricultural settings [192].

8. Agronomic and Environmental Considerations

The integration of PGPMs in sustainable agriculture requires a holistic approach and collaboration among researchers, farmers, and policymakers. PGPMs improve soil structure and retain moisture, facilitating the recovery of degraded soils and increasing agricultural productivity in marginal areas [193,194]. It is important to use native microorganisms adapted to local conditions and to promote practices such as crop rotation and conservation agriculture to enhance soil structure and fertility, reduce diseases and pests, minimize soil disturbance, and promote microbial biodiversity [195]. This reduces erosion, increases carbon retention, and improves water use efficiency [196,197].

PGPMs not only enhance crop productivity but also provide environmental and ecological benefits, such as conserving natural resources and biodiversity. By reducing reliance on agrochemicals, improving soil quality, mitigating climate change, and promoting biodiversity, PGPMs strengthen agricultural systems [142,198]. Some PGPMs naturally control pathogens and pests, minimizing the need for chemical pesticides and reducing soil and water contamination [199,200].

The intensification of chemical pesticide use has led to negative impacts on agricultural productivity, soil fertility, and human health, while also causing long-term contamination of ecosystems [177]. The Green Revolution 2.0 seeks to mitigate these effects through the development of sustainable strategies such as the biodegradation of pesticides by microorganisms, including plant-growth-promoting bacteria (PGPB) consortia, which convert hazardous residues into less harmful metabolites, improving bioavailability in the rhizosphere. Microbial biopesticides and other bioproducts, such as bacteria, fungi, and baculoviruses, are emerging alternatives that promote more sustainable agriculture [201]. Notably, research on endophytic bacteria such as Enterobacter cloacae and Enterobacter sp. has demonstrated their capacity to degrade the pesticide chlorpyrifos, enhancing rice yields through reduced fertilization and bacterial consortia, achieving production increases of up to 39.1%. Chemical analysis has confirmed the degradation of chlorpyrifos into non-toxic metabolites, highlighting its potential as a biostimulant in sustainable agricultural systems [202]. Moreover, pesticides negatively affect the key functions of rhizobacteria, such as nodulation in legumes and nitrogen accumulation, underscoring the need to develop procedures that improve compatibility between microbial inoculants and pesticides. Rhizobacteria represent promising biotechnological tools for the bioremediation of organic pollutants and the reduction of phytotoxic effects on plants via the metabolization of xenobiotics through specialized catabolic enzymes. Advances in microbiology, genetic engineering, and biotechnology can optimize these processes and foster interdisciplinary cooperation in environmental remediation [203].

Additionally, agricultural soils can be contaminated with heavy metals such as arsenic, nickel, and chromium, which negatively impact flora, fauna, and human health due to their association with various diseases. Bioremediation—the utilization of plants and microorganisms—offers a sustainable solution for decontamination. This approach is further supported by advances such as metagenomics, which provide deeper insights into the underlying metabolic processes [204]. Nitrogen-fixing PGPMs reduce the dependence on nitrogen fertilizers and improve soil structure and fertility, increasing water and nutrient retention and reducing erosion [205]. They also promote the activity of beneficial microorganisms, contribute to carbon sequestration and organic matter formation, and enhance the resilience of agroecosystems to diseases, pests, and environmental changes [206,207].

Plant-growth-promoting bacteria (PGPB) offer multiple benefits in agriculture, such as increased crop productivity, improved nutrient availability, and pathogen suppression. Their use, supported by omics data, enables the optimization of inoculants to maximize yields and reduce the dependence on chemical fertilizers, contributing to agricultural sustainability and soil health. However, challenges related to their ecological impacts and potential risks remain. One major concern is the antibiotic resistance observed in many PGPBs. While these genes may be associated with their growth-promoting functions, they could also be horizontally transferred to other soil bacteria, facilitating the spread of anti-biotic resistance genes (ARGs) [208]. This phenomenon is particularly alarming given the interconnectedness of humans, animals, and the environment. Antibiotic resistance—recognized by the WHO as a critical threat to global health—finds favorable conditions for selection and proliferation in agroecosystems, especially when organic fertilizers containing residual antibiotics or resistant bacteria are used. These multidrug-resistant bacteria can reach humans through contaminated food, exacerbating problems in healthcare settings. Recent studies have suggested that using digestate, an organic fertilizer classified as a nature-based solution under European guidelines, could help to mitigate the spread of ARGs in agroecosystems. Furthermore, digestate supports the development of microbe-based solutions, enhancing soil quality and agricultural productivity while reducing the risks associated with ARGs [209].

In the context of plant–microbe interactions, epiphytic, endophytic, and rhizospheric bacteria play key roles in promoting plant growth. Endophytic bacteria, in particular, are recognized for improving nutrient availability, producing growth hormones, and controlling pathogens. Advances in omics techniques, such as metagenomics, metaproteomics, and microRNA analysis, have allowed for the identification of over 400 genes involved in these interactions. Of these, at least 20 genes are linked to endophytism, 50 to growth promotion, 25 to biocontrol, and 10 to abiotic stress mitigation [210]. These findings emphasize the need for further research into the long-term impacts of PGPBs on soil microbial communities and ecosystems, as well as the implementation of strategies to minimize the ecological and health risks associated with their use.

9. PGPM Products Available for Use in Various Crops, Including Rice

The use of PGPBs in bioformulations represents an eco-friendly and cost-effective alternative to chemical fertilizers and pesticides. Notably, various microbe-based or microbial consortium products designed to enhance rice yields are commercially available to farmers worldwide at present [3]. Table S1 (in the Supplementary Materials) describes some of the commercial PGPM products available for use in various crops, including rice.

10. Challenges and Future Perspectives

PGPMs have great potential to improve agricultural productivity and promote sustainability, but they face several challenges. The complexity of interactions between microbes, plants, and soils, along with factors such as edaphoclimatic conditions and agricultural practices, make their identification, characterization, and effective application difficult. Additionally, technological costs, the lack of regulations, and the limited trust of farmers and consumers in their benefits are significant barriers.

Further research is needed in key areas, such as the long-term impact of PGPMs on soil health, their interactions with other microorganisms, and their effects under changing conditions such as those associated with climate change. The environmental risks of their use should also be evaluated.

Technological innovations, such as genetic sequencing and metagenomics, have improved the identification and application of PGPMs. However, further studies are still required to optimize their use and maximize their agricultural benefits.

11. Conclusions

This systematic review has explored the fundamental roles of PGPMs in improving the quality and yield of rice. Multiple mechanisms through which PGPMs benefit plant growth and health have been identified, such as nitrogen fixation, nutrient solubilization, production of growth hormones, and induction of disease resistance. Advances in the identification of effective strains and genetic engineering have also been highlighted. PGPMs represent a promising tool for modern agriculture, particularly in rice cultivation. Their application can enhance the quality and yield of rice through the promotion of plant growth, increasing disease resistance, and improving soil nutrient uptake. These contributions are particularly significant in the context of climate change and environmental pressures, where sustainable agriculture and food security are imperatives.

To maximize the benefits of PGPMs, it is essential to integrate them into sustainable agricultural systems, which will improve soil health, reduce the use of agrochemicals, and promote crop resilience under adverse conditions. Additionally, further exploration is needed regarding the ecophysiological mechanisms underlying the interactions between PGPMs and rice plants, including plant–microorganism communication and the long-term effects of microbial colonization in the rhizosphere. There is also a need to develop PGPM formulations specifically adapted to the needs of rice cultivation, taking into account soil characteristics, climate, and the rice varieties grown in different regions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/ijpb16010009/s1, Table S1: PGPM products available for use in various crops, including rice.

Author Contributions: Conceptualization, W.F.R.-R., H.G.J.-C. and F.R.-R.; writing—original draft preparation, W.F.R.-R., F.R.-R. and E.P.-S.-C.; writing—review and editing, W.F.R.-R., H.G.J.-C., E.E.T.-C., F.R.-R., E.P.-S.-C. and N.E.G.-P. visualization, W.F.R.-R., H.G.J.-C., N.E.G.-P. and E.E.T.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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