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Enhancing Rice Productivity with Plant Growth-Promoting Microorganisms (PGPM)

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Abstract Rice is the primary staple crop in many regions around the world and is crucial for global food security. However, rice production faces numerous challenges, including soil degradation, pest and disease pressure, and climate change issues. Plant Growth-Promoting Microorganisms (PGPM) have shown great potential as a sustainable solution to enhance crop productivity and environmental adaptability. This study analyzes different types of PGPM (bacteria, fungi, and other microorganisms) and their mechanisms of action, highlighting how PGPM can improve soil health and enhance rice productivity. Additionally, through multiple case studies and field trials, this paper demonstrates the effective application of PGPM in actual rice cultivation and compares the outcomes in different ecosystems. This research aims to optimize PGPM application strategies for their widespread use in global rice production, further promoting the sustainable development of agricultural ecosystems.

Keywords *Oryza sativa* L.; Plant growth-promoting microorganisms; Soil health; Sustainable agriculture; Climate change

Rice (*Oryza sativa* L.) is a fundamental staple crop that sustains nearly half of the world's population, particularly in Southeast Asia and other developing regions. It is not only a primary source of calories but also a significant contributor to the socio-economic fabric of many countries. The global demand for rice continues to rise, driven by population growth and dietary preferences (Chen et al., 2023).

Despite its importance, rice production faces numerous challenges. Soil degradation, pest and disease pressures, and climate change are significant hurdles that threaten sustainable rice cultivation. Soil degradation, including nutrient depletion and contamination, adversely affects rice yield and quality. Pest and disease pressures, such as those from insects and pathogens, further complicate rice farming, often necessitating the use of chemical pesticides that can harm the environment (Sundar and Chao, 2022). Additionally, climate change introduces variability in weather patterns, leading to unpredictable water availability and increased incidence of extreme weather events, which can devastate rice crops.

Plant Growth-Promoting Microorganisms (PGPM) are a diverse group of microorganisms, including bacteria, fungi, and microalgae, that enhance plant growth and productivity through various mechanisms (Abhilash et al., 2016; Upadhyay et al., 2018). These microorganisms colonize the rhizosphere, the region of soil surrounding plant roots, and facilitate nutrient uptake, improve soil structure, and enhance plant resistance to stress (Adak et al., 2016; Sundar and Chao, 2022).

The benefits of PGPM in crop production are manifold. They improve nutrient availability and uptake, enhance soil fertility, and increase plant growth and yield. For instance, PGPM can solubilize phosphates, fix atmospheric nitrogen, and produce growth hormones, thereby reducing the need for chemical fertilizers (Pérez-Montaño et al., 2014; Sundar and Chao, 2022). Additionally, they can suppress plant pathogens, thereby reducing the reliance on chemical pesticides. The use of PGPM is particularly beneficial in sustainable agriculture, as it promotes environmental health and reduces the ecological footprint of farming practices (Abhilash et al., 2016).

The study evaluates the potential of Plant Growth-Promoting Microorganisms (PGPM) in enhancing rice yield. This study will analyze and summarize the specific roles and mechanisms of PGPM in improving rice productivity, and explore how these microorganisms can be effectively utilized under different environmental and production conditions to promote a more sustainable and efficient rice production model. Through case studies in various regions and ecosystems, this study aims to identify the optimal strategies for PGPM application, ensuring the effectiveness and feasibility of these biotechnological approaches while taking into account local agricultural practices and environmental factors. Through this comprehensive analysis, this study hopes to provide practical biotechnological solutions for rice production globally, thereby enhancing the health and productivity of agricultural ecosystems.

1 Types of Plant Growth-Promoting Microorganisms

1.1 Bacteria

Plant Growth-Promoting Bacteria (PGPB) are a diverse group of bacteria that colonize plant roots and promote growth through various mechanisms. These include nitrogen fixation, phosphate solubilization, production of phytohormones, and enhancement of stress tolerance.

PGPB such as *Azospirillum brasilense* and *Pseudomonas fluorescens* have been shown to increase nitrogen fixation and nutrient uptake in crops like maize, which can be extrapolated to rice cultivation (Salvo et al., 2018). Salt-tolerant PGPB like *Bacillus pumilus* strain JPVS11 enhance rice growth under salinity stress by improving biochemical and physiological attributes, such as chlorophyll content and antioxidant enzyme activities (Kumar et al., 2020). The combined application of PGPB and arbuscular mycorrhizal fungi (AMF) has been found to significantly improve soil fertility and rice production, indicating the synergistic effects of these microorganisms (Chen et al., 2023).

1.2 Fungi

Arbuscular Mycorrhizal Fungi (AMF) form symbiotic relationships with plant roots, enhancing nutrient uptake, particularly phosphorus, and improving plant resilience to environmental stresses. AMF improve the uptake of essential nutrients like phosphorus, potassium, and nitrogen, which are critical for rice growth. For instance, AMF inoculation has been shown to increase nutrient concentrations in rice tissues and improve overall plant productivity (Chen et al., 2023). AMF also help plants withstand abiotic stresses such as drought and salinity by enhancing root water uptake and altering plant physiology (Emmanuel and Babalola, 2020).

1.3 Others

Other microorganisms, including actinomycetes and yeasts, also contribute to plant growth promotion through various mechanisms. Actinomycetes are known for their ability to decompose organic matter and release nutrients in a form that plants can absorb. They also produce antibiotics that can protect plants from pathogens. Yeasts contribute to plant growth by producing growth-promoting substances such as vitamins and hormones. They also enhance soil health by improving its structure and water-holding capacity (Naik et al., 2019).

In summary, the use of diverse PGPM, including bacteria, fungi, and other microorganisms, offers a sustainable approach to enhancing rice productivity. These microorganisms improve nutrient availability, enhance stress tolerance, and promote overall plant health, leading to increased yields and better crop quality. The synergistic effects of co-inoculation with different types of PGPM further amplify these benefits, making it a promising strategy for sustainable rice cultivation.

2 Mechanisms of PGPM Action

2.1 Nutrient solubilization and uptake

Plant growth-promoting microorganisms (PGPM) enhance nutrient solubilization and uptake in rice plants, leading to improved growth and yield. For instance, *Pantoea ananatis* and *Piriformospora indica* have been shown to significantly increase the uptake of potassium and nitrogen in rice tissues, thereby enhancing nutrient use efficiency (NUE) and grain yield (Bakhshandeh et al., 2017; 2020). Additionally, the combined application of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has been found to increase the availability of essential nutrients such as nitrogen, phosphorus, and potassium in the soil, which in turn boosts rice plant growth and productivity (Chen et al., 2023).

2.2 Production of plant hormones

PGPMs are known to produce various plant hormones that promote growth. For example, *Azospirillum amazonense* produces auxins, which are crucial for root development and overall plant growth. This bacterium has been shown to increase grain dry matter accumulation and the number of panicles in rice plants, primarily through the production of phytohormones. Similarly, other PGPRs produce indole-3-acetic acid (IAA) and other growth-promoting substances that enhance plant growth under stress conditions (Desoky et al., 2020).

2.3 Biological nitrogen fixation

Biological nitrogen fixation (BNF) is a critical mechanism by which PGPMs contribute to plant growth. *Azospirillum amazonense*, for instance, has been shown to fix atmospheric nitrogen, thereby providing an essential nutrient for rice plants. The BNF contribution of *A. amazonense* was measured using the 15N isotope dilution technique, revealing significant nitrogen accumulation in rice grains (Rodrigues et al., 2008). This process not only reduces the need for chemical nitrogen fertilizers but also promotes sustainable agricultural practices.

2.4 Disease suppression

PGPMs also play a vital role in suppressing plant diseases, thereby enhancing plant health and yield. Certain PGPRs exhibit antagonistic activity against plant pathogens such as *Pyricularia oryzae*, the causative agent of rice blast disease. These beneficial microbes produce antimicrobial compounds and lytic enzymes that inhibit the growth of pathogenic species, thereby protecting rice plants from infections (Meena et al., 2017). The mutual interactions between beneficial fungi and pathogenic microbes further contribute to disease suppression and improved plant health.

2.5 Enhancement of stress tolerance

PGPMs enhance the stress tolerance of rice plants by improving their antioxidant defense systems and reducing oxidative stress. For example, PGPRs such as *Bacillus cereus* and *Pseudomonas aeruginosa* have been shown to alleviate salinity stress in wheat plants by enhancing antioxidant activities and reducing oxidative stress biomarkers (Desoky et al., 2020). These mechanisms are likely to be effective in rice as well, helping the plants to withstand various abiotic stresses such as salinity and drought. Additionally, PGPRs improve the physiological attributes of rice plants, including photosynthetic efficiency and water content, thereby enhancing their overall stress tolerance (Desoky et al., 2020).

By leveraging these mechanisms, PGPMs offer a sustainable and eco-friendly approach to enhancing rice productivity and resilience against various biotic and abiotic stresses.

3 PGPM and rice productivity

3.1 Growth promotion

Plant growth-promoting microorganisms (PGPM) have shown significant potential in enhancing the growth of rice plants. Studies have demonstrated that the application of PGPM, such as *Pantoea ananatis* and *Piriformospora indica*, can lead to substantial increases in various growth parameters. For instance, the tiller number per hill, leaf area index, and biomass dry weight were observed to increase by 9.0%~27.2%, 11.7%~45.4%, and 11.1%~24.7%, respectively, when compared to control treatments (Bakhshandeh et al., 2017). Additionally, co-inoculation of Bacillus velezensis and Brevundimonas diminuta has been found to significantly promote rice growth by enhancing the complexity of the microbial network in the rhizosphere, which in turn improves nitrogen absorption and overall plant growth (Figure 1) (Wang et al., 2023).

In the experiment conducted by Wang et al. (2023), rice plants were subjected to different microbial treatments. A visual comparison of the rice plants after treatment showed significant differences in plant vigor and biomass among the four groups. The co-inoculation with *B. velezensis* FH-1 and *B. diminuta* NYM-3(FN) demonstrated the best results, significantly promoting the growth and nutrient absorption of the rice. This finding suggests that microbial consortia may be more effective in agricultural applications, potentially leading to better crop yields and sustainability. The study highlights the potential benefits of using specific microbial combinations to enhance plant growth and nutrient efficiency.

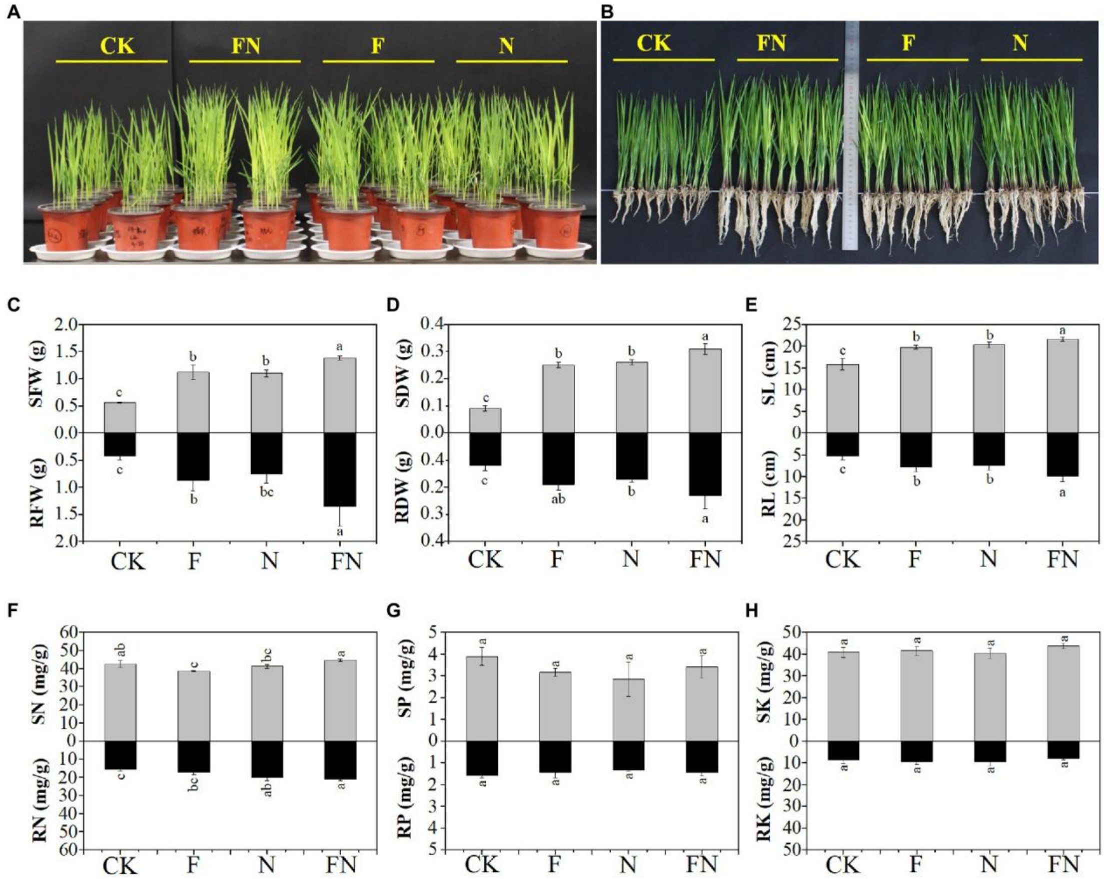

Figure 1 The effects of different microbial inoculants on rice (Adopted from Wang et al., 2023)

Image caption: (A) The rice pot experiments; (B) Photos showing 16-day-old rice plants; (C) Rice shoot (S) and root (R) fresh weight (FW); (D) Rice shoot (S) and root (R) dry weight (DW); (E) Rice shoot (S) and root (R) length (L); (F) Rice shoot (S) and root (R) nitrogen concentration (N); (G) Rice shoot (S) and root (R) phosphorus concentration (P); (H) Rice shoot (S) and root (R) potassium concentration (K); CK, non-inoculated; F, inoculated with *Bacillus velezensis* FH-1; N, inoculated with *Brevundimonas diminuta* NYM-3; FN, inoculated with *B. velezensis* FH-1 and *B. diminuta* NYM-3. Data followed by the different lowercase letters are significantly different at $p \leq 0.05$ (Adopted from Wang et al., 2023)

3.2 Yield improvement

The impact of PGPM on rice yield is profound. Co-inoculation with *Pantoea ananatis* and *Piriformospora indica* has been shown to increase grain yield by approximately 22.6% compared to control treatments (Bakhshandeh et al., 2017). Similarly, the use of PGPM such as *Enterobacter* sp. and *Piriformospora indica* has resulted in a linear increase in grain yield with the addition of potassium sulfate fertilizer, achieving up to 32% higher yields than control treatments (Bakhshandeh et al., 2020). Furthermore, the combined application of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has been reported to significantly boost rice yield and essential nutrient uptake, with a notable increase in nitrogen, phosphorus, and potassium content in plant tissues (Chen et al., 2023).

3.3 Soil health and fertility

PGPM not only enhance plant growth and yield but also play a crucial role in improving soil health and fertility. The application of PGPR and AMF has been shown to lower soil pH and increase the organic matter content, thereby enhancing the availability of essential nutrients such as nitrogen, phosphorus, and potassium in the soil (Chen et al., 2023). Additionally, the use of microbial inoculants like Bacillus amyloliquefaciens and Trichoderma harzianum has been found to improve the utilization of phosphate and other nutrients, leading to increased shoot biomass production and better nutrient acquisition (Mpanga et al., 2018). Coating synthetic NPK fertilizers with plant growth-promoting bacteria has also been demonstrated to improve soil fertility and rice yield under stress conditions, such as alum stress.

In conclusion, the integration of PGPM into rice cultivation practices offers a sustainable approach to enhance rice productivity by promoting plant growth, increasing yield, and improving soil health and fertility. The use of these microorganisms as biofertilizers can significantly contribute to sustainable agricultural practices and food security.

4 Case Studies and Field Trials

4.1 Successful applications of PGPM in rice cultivation

Several case studies have demonstrated the successful application of plant growth-promoting microorganisms (PGPM) in rice cultivation across various regions. For instance, a study conducted on rice (cv. 'Tarom Mahalli') in Iran utilized *Pantoea ananatis* and *Piriformospora indica* to enhance rice growth and yield. The results showed significant improvements in tiller number, leaf area index, biomass dry weight, grain yield, and nutrient uptake, with co-inoculation proving to be the most effective treatment (Bakhshandeh et al., 2017). Another field experiment in Egypt evaluated the effects of *Pantoea ananatis*, *Enterobacter* sp., and *Piriformospora indica* on rice productivity. The study found that co-inoculation significantly increased grain yield and nutrient use efficiency, particularly when combined with potassium sulfate fertilizer (Bakhshandeh et al., 2020).

In India, a field experiment assessed the impact of Anabaena-based biofilm inoculants on micronutrient enrichment in rice grown under conventional and System of Rice Intensification (SRI) practices. The study reported enhanced nutrient uptake, enzyme activity, and yield, with significant increases in iron and zinc concentrations in rice grains (Adak et al., 2016). Additionally, research in Pakistan explored the combined application of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) on soil fertility and rice production. The results indicated improved nutrient availability, soil health, and rice yield (Figure 2) (Chen et al., 2023).

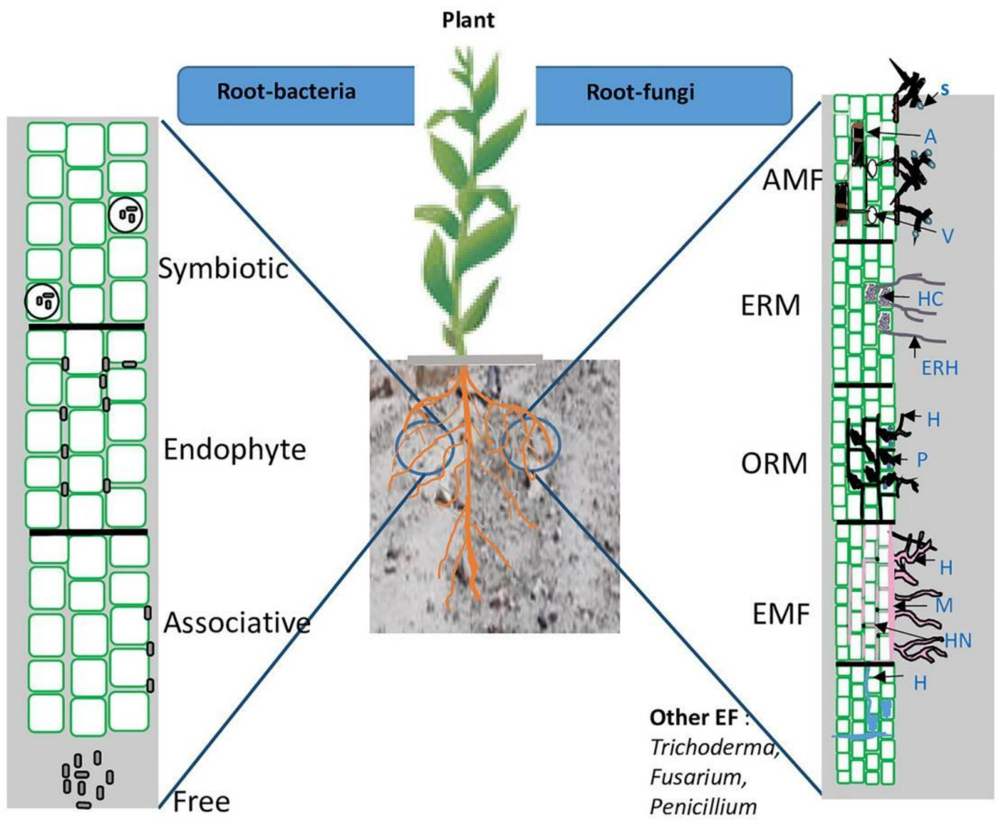

Figure 2 Schematic representation of root and rhizosphere colonization by beneficial microorganisms (Adopted from Soumare et al., 2021)

Image caption: AMF, arbuscular mycorrhizal fungi; ERM, ericoid mycorrhizal fungi; OMF, orchid mycorrhizal fungi; EMF, ectomycorrhizal fungi; EF, endophyte fungi; A, arbuscules; ERH, extraradical hyphae; V, vesicles; S, spore; HC, hyphal coils; P, peloton; HN, Hartig net; and M, mantle (Adopted from Soumare et al., 2021)

The study by Soumare et al. (2021) emphasizes that PGPR enhances plant growth and increases plant resistance to pests and diseases through mechanisms such as nitrogen fixation, phosphate solubilization, and the production of plant hormones. Meanwhile, AMF enhance plant nutrient uptake efficiency, such as phosphorus, by expanding the root absorption area and improving plant stress tolerance. The illustration shows the different sites and mechanisms of action of PGPR and AMF in the roots and soil, demonstrating their synergistic effects, which significantly improve nutrient utilization, soil health, and yield in rice. This combined application not only optimizes resource use but also sustainably enhances agricultural productivity.

4.2 Comparative studies

Comparative studies have consistently shown that PGPM-treated rice fields outperform untreated fields in terms of growth, yield, and nutrient uptake. For example, a study comparing PGPM-treated and untreated rice fields found that PGPM-treated fields had significantly higher dry weight, grain yield, and nutrient uptake, particularly when co-inoculation methods were used (Bakhshandeh et al., 2020). Another study highlighted the superior performance of PGPM-treated fields in terms of micronutrient enrichment and enzyme activity, leading to better overall plant health and productivity (Adak et al., 2016).

A meta-analysis of multiple studies on the application of PGPM in rice cultivation reveals consistent positive outcomes. The use of PGPMs, such as *Pantoea ananatis*, *Piriformospora indica*, and Anabaena-based biofilm inoculants, has been shown to enhance rice growth, yield, and nutrient uptake across different regions and cultivation practices (Adak et al., 2016; Bakhshandeh et al., 2017; 2020; Chen et al., 2023). The combined application of PGPR and AMF has also been effective in improving soil fertility and rice production, further supporting the potential of PGPMs as biofertilizers in sustainable agriculture .

In summary, the application of PGPMs in rice cultivation has demonstrated significant benefits in terms of growth, yield, and nutrient uptake. Comparative studies and meta-analyses confirm the efficacy of PGPMs in enhancing rice productivity, making them a valuable tool for sustainable agriculture.

5 Challenges and Limitations

5.1 Variability in PGPM performance

One of the primary challenges in utilizing plant growth-promoting microorganisms (PGPM) is the variability in their performance under different environmental conditions. The effectiveness of PGPM can be influenced by several factors, including soil type, nutrient availability, and climatic conditions. For instance, the study by Bakhshandeh et al. (2017) demonstrated that the co-inoculation of *Pantoea ananatis* and *Piriformospora indica* significantly improved rice growth and yield, but the results varied depending on the levels of potassium sulfate fertilizer used. Similarly, Wang et al., (2023) highlighted that the co-inoculant *Bacillus velezensis* FH-1 and Brevundimonas diminuta NYM3 promoted rice growth by regulating the rhizosphere microbiome, but the extent of this promotion was influenced by the specific soil conditions. These findings underscore the need for site-specific assessments to optimize the use of PGPM in different agricultural settings (Figure 3).

Soumare et al. (2021) compared the applications of traditional micropropagation processes and bio-enhanced processes in plant tissue culture. In the traditional micropropagation process, plant explants undergo elongation and proliferation, relying on plant growth regulators such as auxins and cytokinins for rooting and acclimatization stages, before being transplanted into the field. However, this method has a problem with low survival rates. In contrast, the bio-enhanced process introduces beneficial microbes, such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR), which play an important role during the plant elongation, proliferation, and rooting stages. Plants bio-enhanced in this way exhibit better growth during the acclimatization stage and significantly improved survival rates after transplantation to the field.

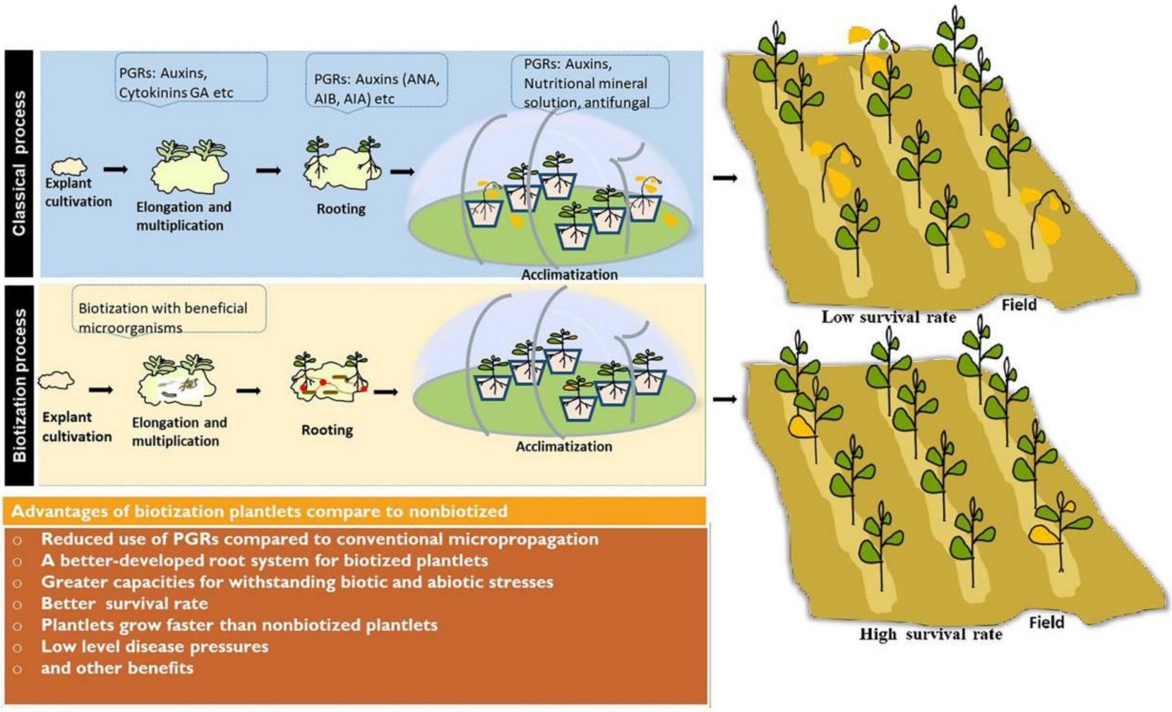

Figure 3 Some benefits of biotization process compared to classical micropropagation process (Adopted from Soumare et al., 2021)

5.2 Practical applications

The practical application of PGPM in rice cultivation faces several hurdles. One significant issue is the inconsistent vitality and efficiency of PGPM when applied as biofertilizers. For example, Ji et al. (2019) explored the use of atmospheric pressure non-thermal plasma to enhance the vitality and functional activity of Bacillus subtilis CB-R05, which subsequently improved rice growth and yield. However, such technological interventions may not always be feasible or cost-effective for large-scale farming. Additionally, the method of inoculation plays a crucial role in the success of PGPM applications. According to Lopes et al. (2021), different inoculation methods, such as seed, root, and soil inoculation, can lead to varying outcomes in plant growth and stress tolerance. Therefore, developing standardized and efficient inoculation techniques is essential for the widespread adoption of PGPM in agriculture.

5.3 Regulatory and safety issues

The use of PGPM in agriculture also raises regulatory and safety concerns. Ensuring that these microorganisms do not pose any risks to human health, non-target organisms, or the environment is paramount. The study by Soumare et al. (2021) emphasized the need for stringent regulatory frameworks to oversee the application of PGPM, particularly in micropropagation and other controlled environments. Moreover, the potential for horizontal gene transfer and the development of antibiotic resistance in microbial communities necessitates careful monitoring and regulation. As highlighted by Cavite et al. (2020), further field evaluations are required to confirm the safety and efficacy of PGPM before they can be recommended as biofertilizers on a large scale. Addressing these regulatory and safety issues is crucial for gaining public trust and ensuring the sustainable use of PGPM in enhancing rice productivity.

6 Conclusions and Prospects

Research on Plant Growth-Promoting Microorganisms (PGPM) has demonstrated significant potential in enhancing rice yield. Numerous studies have shown that PGPM can improve growth parameters such as tiller number, leaf area index, dry biomass, and grain yield. For instance, co-inoculation with *Pantoea ananatis* and *Piriformospora indica* has been shown to increase grain yield by 22.6% and reduce the usage of potassium sulfate fertilizer by 40.5%. Similarly, the *Bacillus subtilis* strain JPVS11 has been proven to enhance plant height, root length, chlorophyll content, and soil enzyme activity under salinity stress.

The combined application of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has also been effective in improving soil fertility and rice yield. Recent advancements in genomics and biotechnological methods have facilitated the development of more efficient PGPM strains. Molecular characterization of strains such as *Bacillus subtilis* JPVS11 has identified key plant growth-promoting traits such as production of indole-3-acetic acid and ACC deaminase activity, which are crucial for stress resistance and nutrient uptake. Furthermore, mathematical models describing the impact of PGPM on rice growth and yield offer new insights into their physiological effects.

PGPM are increasingly being integrated with sustainable agricultural practices, such as organic farming and integrated pest management. Using PGPM as biofertilizers can reduce dependence on chemical fertilizers, thereby minimizing environmental impact and promoting soil health. Studies have shown that PGPM can enhance nutrient use efficiency and improve soil enzyme activity, making them a viable option for sustainable rice production systems. Combining PGPM with other sustainable practices like organic farming and integrated pest management can further enhance their effectiveness. For example, combining PGPM with reduced chemical fertilizer application has been shown to maintain or even increase rice yield while reducing environmental impact. Moreover, integrating PGPM with practices such as crop rotation and cover cropping can improve soil health and resistance to pests and diseases.

PGPM hold tremendous potential in enhancing rice yield and ensuring global food security. By improving nutrient absorption, stress resistance, and soil health, PGPM can play a key role in sustainable agriculture. Future research should focus on optimizing inoculation techniques, understanding the mechanisms of plant-microbe interactions, and developing multi-strain inoculants to maximize the benefits of PGPM. With ongoing advances in genomics and biotechnological methods, PGPM can make significant contributions to sustainable food production and global food security.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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