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Mitigating Salinity, Drought, and Heavy Metal Stress in Rice Using Plant Growth-Promoting Bacteria

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Abstract

Rice (*Oryza sativa L.),* a staple providing calories for over half the global population, faces escalating threats from abiotic stresses salinity (affecting 20% of irrigated lands), drought, and heavy metal contamination (As, Cd, Pb) projected to cause 50–70% yield losses amid climate change and a 2050 population surge to 10 billion. Conventional breeding and genetic engineering face limitations in conferring multi-stress tolerance due to polygenic traits and regulatory hurdles. This review elucidates the pivotal role of plant growth-promoting bacteria (PGPB) as sustainable bio-tools for enhancing rice resilience. PGPB employ direct mechanisms including phytohormone production (IAA, gibberellins, cytokinins), nutrient mobilization (N-fixation, P/Zn-solubilization, siderophores), and ACC deaminase-mediated ethylene reduction to sustain root architecture, photosynthesis, and nutrient uptake. Indirect pathways involve pathogen suppression via antimicrobials (HCN, VOCs) and induced systemic resistance (ISR) through JA/ethylene signaling, boosting antioxidants (phenolics, flavonoids) and ROS scavenging. Under salinity, PGPB modulate ion transporters (SOS, HKT, NHX, H+-ATPase) to maintain low Na+/K+ ratios and osmotic balance via exopolysaccharides and osmoprotectants. Drought tolerance is augmented by improved water retention, stomatal regulation, and ABA signaling, while heavy metal detoxification occurs through biosorption, methylation (As), and chelation, reducing grain accumulation. Synergistic PGPB consortia (*Bacillus, Pseudomonas, Azospirillum*) yield superior outcomes, with field trials showing 15–50% yield gains. Challenges include strain specificity, environmental variability, and commercialization barriers, yet PGPB integration with agronomic practices offers eco-friendly pathways for climate-resilient rice production.

Keywords: Plant Growth-Promoting Bacteria (PGPB), Rice (Oryza sativa), Salinity Stress, Drought Tolerance, Heavy Metal Detoxification, ACC Deaminase, Phytohormones, Induced Systemic Resistance (ISR), Ion Homeostasis, Sustainable Agriculture

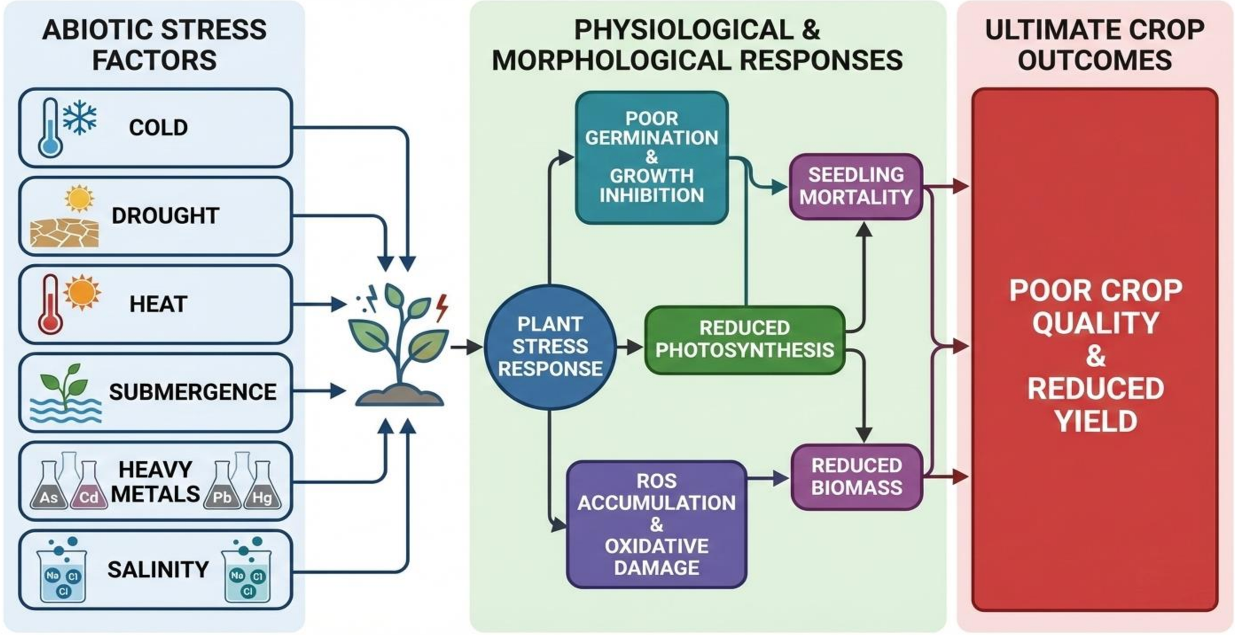
1. Introduction: The Global Imperative for Abiotic Stress Mitigation in Rice Agroecosystems

The cultivation of rice (*Oryza sativa*) occupies a central position in global food security, providing the primary source of calories for more than half of the world's population. However, the stability of rice production is increasingly threatened by an intensifying nexus of environmental pressures. As the global population is projected to reach 10 billion by 2050, the demand for rice is expected to escalate concomitantly, yet the expansion of arable land is constrained by urbanization and environmental degradation (Thakur et al., 2024). Climate change further exacerbates this predicament by increasing the frequency and severity of abiotic stressors, specifically soil salinity, prolonged drought, and heavy metal contamination (Hussain et al., 2022). These stressors are estimated to account for 50% to 70% of potential yield losses in cereal crops globally (Khan et al., 2025).

The vulnerability of rice to environmental perturbations is deeply rooted in its physiological and developmental characteristics. Unlike many other cereals, rice is often grown in flooded conditions, making its rhizosphere chemistry and microbial dynamics unique and highly sensitive to changes in soil redox potential and water availability (Mohapatra et al., 2025). Salinity affects approximately 20% of the world's irrigated land, leading to osmotic stress and ion toxicity that disrupt vital cellular processes (Das et al., 2025). Drought, a multidimensional stressor, reduces cell turgor and induces oxidative damage through the accumulation of reactive oxygen species (ROS). Simultaneously, the anthropogenically driven accumulation of heavy metals such as arsenic (As), cadmium (Cd), and lead (Pb) in paddy soils not only impairs plant growth but also introduces toxic elements into the human food chain (Zhang et al., 2022).

Traditional strategies to combat these stresses, including conventional breeding and genetic engineering, have encountered significant hurdles. Breeding for multi-stress tolerance is complex due to the polygenic nature of these traits and the often-conflicting physiological requirements for different stress responses (Ramadhona, 2025). Genetic engineering, while powerful, faces high costs, lengthy regulatory processes, and public skepticism. In this context, the utilization of plant growth-promoting bacteria (PGPB) has emerged as a transformative, eco-friendly, and sustainable biological tool. PGPB facilitate plant resilience through a sophisticated array of mechanisms, including the production of phytohormones, the reduction of stress-induced ethylene via 1-aminocyclopropane-1-carboxylate (ACC) deaminase, and the modulation of the plant's antioxidant and ion transport systems (Zampieri et al., 2023).

Figure 1: Impact of Abiotic Stressors on Rice Physiology, Morphology, and Yield Outcomes.



2. The PGPB Biological Toolkit: Mechanisms of Growth Promotion and Stress Tolerance

Plant growth-promoting bacteria are a heterogeneous group of microorganisms inhabiting the rhizosphere, phyllosphere, or the interior of plant tissues as endophytes. These beneficial bacteria establish intricate molecular dialogues with their hosts, often initiated by the sensing of root exudates (George et al., 2024). The mechanisms through which PGPB enhance rice growth and resilience can be categorized into direct and indirect pathways, both of which are critical for survival in adverse environments (Khatibi et al., 2024).

2.1 Direct Mechanisms of Phytohormone Modulation and Nutrient Acquisition

The direct promotion of plant growth by PGPB involves the enhancement of nutrient availability and the modulation of the plant's endogenous hormonal balance. Phytohormones such as auxins, gibberellins, and cytokinins are pivotal in regulating development and stress responses (Orozco-Mosqueda et al., 2023).

Table 1: Direct Mechanisms of Plant Growth Promotion by PGPB

Mechanism	**Biological Process**	**Key Regulatory Components**
Nitrogen Fixation	Conversion of atmospheric N2 into NH3	Nitrogenase enzyme complex
Phosphate Solubilization	Release of bound P via organic acid secretion	Gluconic, citric, and malic acids
Auxin Production	Tryptophan-dependent synthesis of IAA	Indole-3-acetic acid (IAA)
Gibberellin Synthesis	Diterpene production via mevalonic acid path	GA3 and other gibberellins
Cytokinin Production	Modified adenine synthesis	Zeatin and related compounds

Indole-3-acetic acid (IAA) is the most ubiquitous auxin produced by PGPB. It stimulates the elongation of the primary root and the proliferation of lateral and adventitious roots. This architectural modification significantly increases the total root surface area, enhancing the plant's capacity to absorb water and essential minerals a trait that is particularly beneficial during drought and salinity stress (Rariz et al., 2017). Furthermore, PGPB synthesize gibberellins that promote stem elongation and break seed dormancy, and cytokinins that delay leaf senescence by maintaining chlorophyll integrity and photosynthetic activity (Shultana et al., 2021).

Nutrient acquisition is another cornerstone of direct growth promotion. PGPB facilitate the uptake of essential elements through biological nitrogen fixation and the solubilization of inorganic phosphorus, potassium, and zinc (Timofeeva et al., 2024). Zinc-solubilizing strains of *Bacillus* have been shown to improve the yield of Basmati rice by up to 22%. Additionally, many PGPB secrete siderophores high-affinity iron-chelating compounds that sequester ferric iron (Fe3+) from the environment, making it available to the plant while depriving phytopathogens of this vital resource (EL Sabagh et al., 2022).

2.2 The Role of ACC Deaminase in Stress Ethylene Regulation

A critical molecular intervention by PGPB under abiotic stress is the production of the enzyme ACC deaminase. In response to stressors like salinity and drought, plants increase the synthesis of 1-aminocyclopropane-1-carboxylic acid (ACC), the immediate precursor to ethylene (Ahmad et al., 2024). While ethylene is essential for normal growth, its overproduction under stress induces senescence, inhibits root elongation, and accelerates cell death (Jamal et al., 2024).

ACC deaminase-producing bacteria cleave ACC into ammonia and alpha-ketobutyrate, thereby effectively lowering the internal ethylene levels of the host plant. This enzymatic activity preserves root development and allows the plant to maintain growth even under severe osmotic or ionic stress (Chandwani et al., 2022). Research indicates that inoculation with ACC deaminase-producing *Enterobacter* and *Bacillus* strains significantly enhances rice germination and seedling vigor under cadmium and salinity stress (Naing et al., 2021).

2.3 Indirect Mechanisms and Induced Systemic Resistance

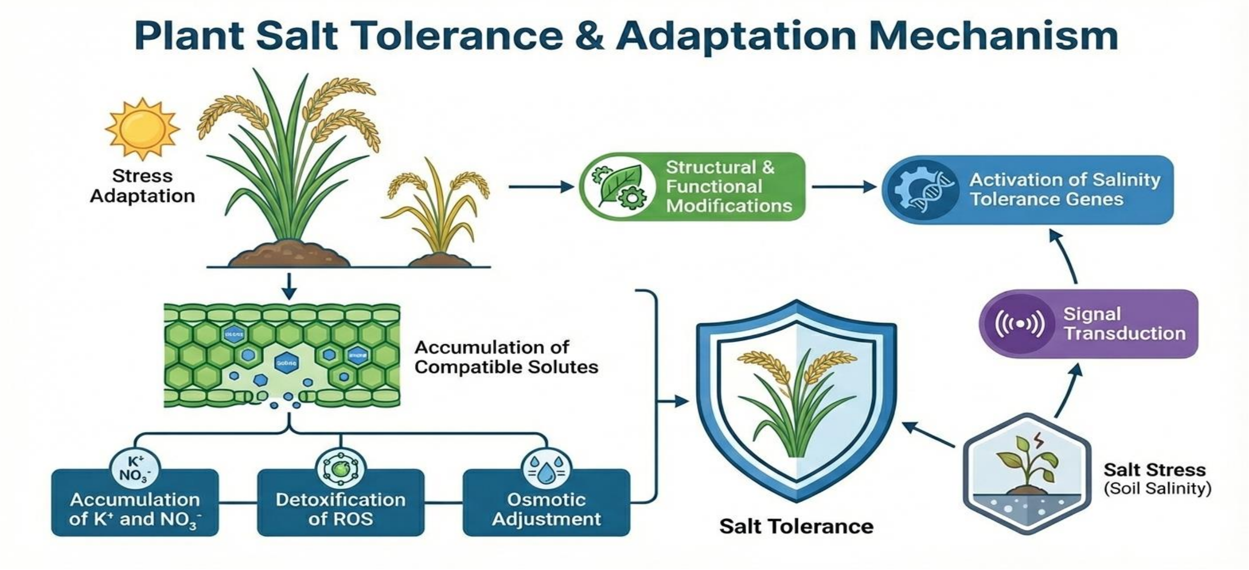
Indirect growth promotion primarily involves the suppression of phytopathogens and the induction of systemic resistance. PGPB compete with pathogens for space and nutrients in the rhizosphere and produce antimicrobial metabolites, including antibiotics, hydrogen cyanide (HCN), and volatile organic compounds (VOCs) (Ajinde et al., 2024). These interactions are not only vital for biocontrol but also contribute to the plant's overall resilience against abiotic factors (Meena et al., 2020).

PGPB trigger Induced Systemic Resistance (ISR), which primes the plant's defense machinery across all tissues. ISR activation typically involves jasmonic acid (JA) and ethylene signaling pathways, leading to the upregulation of genes involved in the phenylpropanoid pathway (Hamid et al., 2021). This results in the increased production of phenolic compounds and flavonoids, such as quercetin and caffeic acid, which act as potent antioxidants to neutralize ROS generated during drought and heavy metal stress (Ajijah et al., 2023). Studies have shown that PGPB can increase the content of these secondary metabolites by 9% to over 200%, significantly bolstering the plant's adaptive capacity (Dobrzynski & Nazieblo, 2024).

3. Navigating Salinity Stress: Ion Homeostasis and Molecular Reprogramming

Salinity is one of the most pervasive abiotic stresses in rice farming, particularly in coastal regions where seawater intrusion is common. Rice is generally considered salt-sensitive, especially during the early seedling and reproductive stages (Win et al., 2022). Salinity imposes two distinct types of stress: an immediate osmotic stress that limits water uptake and a long-term ionic stress caused by the toxic accumulation of sodium (Na+) ions (Rahman et al., 2021).

Figure 2: Molecular and Physiological Pathways for Plant Salt Tolerance and Ion Homeostasis.



3.1 Molecular Regulation of Sodium Transport and the Na+/K+ Ratio

The maintenance of a low cytosolic Na+/K+ ratio is the hallmark of salt tolerance in rice. Sodium ions compete with potassium (K+) for binding sites on metabolic enzymes, disrupting protein synthesis and photosynthetic electron transport. Rice plants utilize a suite of transporters to regulate ion flux, many of which are modulated by PGPB inoculation (Farooq et al., 2021).

Table 2: Key Ion Transporters Modulated by PGPB under Salinity Stress

Transporter Family	**Primary Function**	**Relevant Genes**
SOS (Salt Overly Sensitive)	Na+ exclusion from the root to the soil	OsSOS1
HKT (High-affinity K+ Transporter)	Na+ retrieval from xylem; phloem loading	OsHKT1;1, OsHKT1;5, OsHKT2;1
NHX (Na+/H+ Antiporter)	Vacuolar sequestration of Na+	OsNHX1 to OsNHX5
H+-ATPase	Generating proton gradient for ion exchange	OsVHA

The Salt Overly Sensitive (SOS) pathway is central to sodium exclusion. It involves a Ca2+-sensing protein (SOS3) and a kinase (SOS2) that activate the plasma membrane Na+/H+ antiporter SOS1. SOS1 extrudes Na+ from the cytoplasm to the rhizosphere, a process driven by the proton gradient created by H+-ATPases (Xie et al., 2025). PGPB such as *Bacillus tequilensis* UPMRB9 and *Bacillus aryabhattai* UPMRE6 have been shown to reduce the Na+/K+ ratio in rice, thereby protecting photosynthetic pigments and maintaining stomatal conductance (Shultana et al., 2021). Furthermore, the HKT family of transporters plays a vital role in long-distance sodium transport. *OsHKT1;5* is specifically responsible for retrieving Na+ from the xylem sap in the root stele, preventing its translocation to the photosynthetic tissues in the shoot (Sridhar et al., 2025). Salt-tolerant cultivars like Pokkali exhibit high expression of these transporters, and research indicates that PGPB can positively modulate the expression of *OsHKT* genes even in sensitive varieties, effectively mimicking the tolerance mechanisms of halophytes (Sun et al., 2025).

3.2 Osmotic Adjustment and the Accumulation of Compatible Solutes

To counter the osmotic component of salinity stress, rice plants accumulate compatible solutes small, non-toxic organic molecules that lower the intracellular osmotic potential to facilitate water uptake (Tiwari et al., 2017). PGPB inoculation significantly enhances the synthesis of these osmoprotectants, most notably proline, glycine betaine, and total soluble sugars (Sánchez et al., 2023).

Proline accumulation is a well-documented response to osmotic stress. It acts as a molecular chaperone that protects protein structures and membranes from denaturation and serves as a direct scavenger of hydroxyl radicals (Gupta et al., 2022). Experimental evidence using *Bacillus amyloliquefaciens* strain NBRI-SN13 demonstrated a robust, time-dependent increase in proline and soluble sugar content across multiple stressors, including salinity and heat. This biochemical priming by PGPB helps maintain cell turgor and metabolic integrity when soil water potential is critically low (Gamalero et al., 2022).

3.3 The Protective Role of Exopolysaccharides and Biofilms

The production of exopolysaccharides (EPS) by PGPB provides an additional layer of protection against salinity. EPS are complex carbohydrate polymers that form a protective biofilm around the roots (Alhoqail, 2025). These biofilms serve several functions: they improve the water-holding capacity of the rhizosphere, facilitate soil aggregation, and act as a cation exchanger that can physically bind Na+ ions, thereby reducing their bioavailability and influx into the root system

(Morcillo et al., 2021). By creating a hydrated and ion-buffered microenvironment, EPS-producing PGPB allow rice seedlings to maintain higher relative water content (RWC) and membrane stability even in saline-affected soils (Bhagat et al., 2021).

4. Drought Resilience: Enhancing Water Use Efficiency and Antioxidant Capacity

Drought is a primary constraint on rice productivity, particularly in rain-fed upland and lowland systems. The plant's response to drought is complex, involving morphological adaptations, physiological adjustments, and molecular signaling. PGPB play a multifaceted role in enhancing drought tolerance, primarily through root engineering and the stabilization of the cellular redox state (Gamalero et al., 2022).

4.1 Root Architectural Plasticity and Water Uptake

One of the most immediate effects of PGPB inoculation under drought is the modification of the root system architecture. Driven largely by bacterial IAA production, inoculated rice plants exhibit increased root length, surface area, and lateral root density. This expansion allows the plant to tap into deeper soil moisture reserves that would otherwise be inaccessible (Rariz et al., 2017).

In addition to traditional flooding, many modern rice systems employ Alternate Wetting and Drying (AWD) irrigation to save water. While AWD can reduce water use by up to 30%, it can also induce mild drought stress that impacts yield. Integrating PGPB into AWD systems has shown promising results in maintaining productivity by enhancing nutrient acquisition and root development during the drying cycles (Sridhar et al., 2025).

4.2 Scavenging of Reactive Oxygen Species (ROS)

Drought stress leads to the excessive production of ROS, including superoxide radicals (O2-), hydrogen peroxide (H2O2), and hydroxyl radicals (OH.). These species cause lipid peroxidation, protein degradation, and DNA damage. PGPB mitigate this oxidative damage by upregulating the plant's antioxidant defense systems (Ramadhona, 2025).

Table 3: Antioxidant Components Involved in Drought Stress Mitigation

Antioxidant Component	Function in Stress Mitigation	Specific Enzymes/Compounds
Enzymatic Defense	Direct detoxification of ROS	SOD, CAT, POD, APX, GR
Non-Enzymatic Defense	Free radical scavenging and redox buffering	Ascorbate, Glutathione, Flavonoids
Secondary Metabolites	UV protection and antioxidant activity	Phenolic acids, Quercetin

Superoxide dismutase (SOD) serves as the first line of defense, converting superoxide radicals into hydrogen peroxide, which is subsequently neutralized by catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) (Islam et al., 2022). PGPB strains like *Providencia vermicola* ME1 and *Pantoea agglomerans* Pa have been shown to modulate these enzyme activities in rice and wheat, leading to reduced levels of malondialdehyde (MDA), a key indicator of lipid peroxidation (Saxena et al., 2022).

4.3 Volatile Organic Compounds (VOCs) and Systemic Tolerance

PGPB emit a diverse array of VOCs, such as acetoin and 2, 3-butanediol, which act as airborne signaling molecules. These compounds can trigger Induced Systemic Tolerance (IST) by modulating the plant's hormonal pathways (Timofeeva et al., 2024). For example, certain VOCs can influence the production and signaling of abscisic acid (ABA), the primary hormone responsible for stomatal closure. By optimizing stomatal behavior, PGPB help the plant minimize transpirational water loss while maintaining enough gas exchange for photosynthesis (Laller et al., 2023).

5. Mitigation of Heavy Metal Toxicity and Translocation

Heavy metal contamination, particularly by arsenic, cadmium, and lead, poses a severe threat to rice productivity and human health. Rice's ability to accumulate these metals is enhanced by the anaerobic conditions of flooded paddies, which increase the mobility and toxicity of certain elements. PGPB offer a promising bioremediation strategy by reducing the bioavailability of these metals in the soil and blocking their translocation to the grain (Zhang et al., 2022).

5.1 Arsenic Speciation and Bioavailability in Paddy Soils

Arsenic (As) is a major concern in many rice-growing regions. In flooded soils, inorganic arsenite (As (III)) is the predominant species. Because As (III) is a chemical analogue of silicic acid, it enters rice plants through silicon transporters like *OsLsi1* and *OsLsi2* (Wisawapipat et al., 2021).

PGPB can mitigate arsenic toxicity through several specialized mechanisms:

- **Oxidation:** Bacterial strains can oxidize the more mobile and toxic As(III) to As(V), which is more readily adsorbed onto iron plaques formed on the root surface (Kumarathilaka et al., 2020).
- **Methylation:** Microbes can facilitate the methylation of inorganic arsenic into less toxic organic forms like dimethylarsinic acid (DMA), which can be volatilized or sequestered (Chen et al., 2020).
- **Sequestration in Iron Plaques:** PGPB enhance the formation of iron plaques a layer of iron oxides on the root surface which acts as a "buffer" or "trap" for arsenic, preventing its entry into the root vascular system (Housh et al., 2021).
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5.2 Cadmium and Lead Detoxification Pathways

Cadmium (Cd) is highly mobile and is translocated from roots to shoots and grains via the xylem and phloem. Lead (Pb) is less mobile but induces severe DNA damage and inhibits chlorophyll biosynthesis (Ramadhona, 2025).

PGPB mitigate these metals through:

- **Extracellular Sequestration:** Bacteria use their EPS and cell wall components to bind metal ions, effectively immobilizing them in the soil (Hussain et al., 2022).
- **Modulation of Transporters:** PGPB can influence the expression of heavy metal transporters, such as ABC transporters and NRAMP genes. For instance, the *OsABCC9* gene is involved in the vacuolar sequestration of Cd in rice roots, and its expression can be influenced by microbial interactions (Yang et al., 2021).
- **Resistance Mechanisms:** Strains like *Enterobacter* sp. S2 and K2 exhibit multi-heavy-metal resistance (to Cd, Pb, As, Ni, and Hg) and possess high levels of ACC deaminase and IAA, which help the plant survive in contaminated environments while reducing metal accumulation in edible tissues (; Al-Huqail et al., 2025).
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Table 4: PGPB-Mediated Mechanisms for Reducing Heavy Metal Toxicity and Translocation in Rice

Metal	Primary Mechanism of Reduction	Impact on Grain Quality
Arsenic (As)	Biotransformation (oxidation/methylation)	Lower inorganic As content

Cadmium (Cd)	Vacuolar sequestration and efflux	37% to 50% reduction in grain Cd
Lead (Pb)	Immobilization in rhizosphere and root cells	Protection of genomic stability (GTS)

Recent studies using genomic template stability (GTS) analysis have shown that Pb stress causes significant DNA damage in rice, but the application of PGPB can mitigate these effects by reducing lead uptake and enhancing the plant's repair mechanisms (Aslam et al., 2021).

6. The Comparative Efficacy of Major PGPB Genera in Rice

While many bacterial genera possess PGP traits, three groups *Bacillus*, *Pseudomonas*, and *Azospirillum* are most frequently utilized in rice research and commercial applications (Khan et al., 2025).

6.1 Bacillus spp.: The Resilience Experts

Bacillus species are Gram-positive, rod-shaped bacteria known for their ability to form endospores. This developmental trait allows them to survive extreme heat, desiccation, and chemical stress, making them ideal candidates for commercial biofertilizers. Strains such as *Bacillus amyloliquefaciens* NBRI-SN13 and *Bacillus pumilus* TUAT-1 have demonstrated remarkable success in field trials (Shultana et al., 2021).

In salinity trials, *B. pumilus* TUAT-1 combined with nitrogen fertilizer increased grain yield by 15% under 100 mM NaCl stress. *Bacillus* strains are also proficient in producing antimicrobial lipopeptides like surfactin and iturin, which provide high-level biocontrol against diseases like bacterial leaf blight. Their ability to produce robust biofilms is particularly effective for drought mitigation (Win et al., 2022).

6.2 Pseudomonas spp.: Metabolic Versatility and Fast Growth

Pseudomonas species are Gram-negative, highly mobile bacteria that excel at colonizing the rhizosphere. They are known for their diverse metabolic pathways and the production of a wide range of secondary metabolites, including siderophores and VOCs (Ramos-Hegazy et al., 2021).

Strains like *Pseudomonas fluorescens* Pf1 are widely used for the biocontrol of *Xanthomonas oryzae* and for promoting growth under salt stress. *Pseudomonas* is also a major producer of ACC deaminase and phenolic compounds, contributing significantly to Induced Systemic Resistance (Dobrzynski & Nazieblo, 2024). However, unlike *Bacillus*, they do not form spores, which can make their survival in dry or saline soils more challenging without specialized formulations (Santoyo et al., 2024).

6.3 Azospirillum spp.: Phytohormone Powerhouses

Azospirillum is perhaps the most well-known genus for asymbiotic nitrogen fixation in cereal crops. It is characterized by its ability to produce exceptionally high levels of IAA, which can dramatically transform the rice root system (Rariz et al., 2017).

Strains like *Azospirillum brasilense* Az39 are common in commercial inoculants. They improve yields by enhancing nutrient use efficiency and root-based water acquisition. While highly effective at growth promotion, their role in heavy metal remediation is generally considered less potent compared to specialized bioremediating genera like *Enterobacter* or *Cupriavidus* (Todorov et al., 2022).

7. Advanced Strategies: Microbial Consortia and Multi-Omics Integration

The future of PGPB application in rice cultivation is shifting from single-strain inoculants to the development of complex microbial consortia and Synthetic Communities (SynComs). These consortia aim to harness the synergistic interactions between different functional groups of bacteria to provide more stable and multifaceted stress protection (Khan et al., 2025).

7.1 Host-Mediated Selection (HMS) and the "Cry for Help" Strategy

Innovative techniques such as Host-Mediated Selection allow researchers to iteratively select for microbiomes that enhance a specific trait, such as drought tolerance, over multiple generations. This approach relies on the "cry for help" strategy, where plants under stress modify their root exudate profiles to specifically recruit and nourish beneficial microbes (George et al., 2024).

By analyzing the chemistry of these exudates such as the C/N ratio and specific organic acids researchers can develop a "Love Match" score to predict the compatibility between a rice cultivar and a PGPB strain. This ensures that the introduced bacteria can effectively colonize and persist in the rhizosphere under stressful conditions (Islam et al., 2022).

7.2 Multi-Omics and Metagenomic Insights

The integration of multi-omics technologies is providing a high-resolution view of the molecular dialogue between PGPB and rice (Farooq et al., 2021).

- **Transcriptomics:** Identifying the upregulation of master regulatory transcription factors like *OsNAC6* and *OsDREB* in response to PGPB (Alhoqail, 2025).
- **Proteomics:** Mapping changes in the abundance of antioxidant enzymes and ion transporters (Ajijah et al., 2023).
- **Metabolomics:** Characterizing the synthesis of stress-responsive metabolites, including osmolytes and signaling VOCs (Ramos-Hegazy et al., 2021).
- **Metagenomics assembled genomes (MAGs):** Understanding the origins and transmission of heavy metal resistance genes from seeds and the environment (Bhagat et al., 2021).
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8. Translational Challenges: The "PGPB Paradox" and Implementation Hurdles

Despite the overwhelming success of PGPB in laboratory and greenhouse settings, their translation to field conditions is often inconsistent a phenomenon termed the "PGPB Paradox" (Xie et al., 2025). Several factors contribute to this discrepancy:

- **Ecological Incompatibility:** Inoculated strains must compete with the native microbial community, which is already adapted to the local environment (Sun et al., 2025).
- **Environmental Variability:** Field conditions are characterized by fluctuating moisture, temperature, and nutrient levels that can impair bacterial survival (Gamalero et al., 2022).
- **Formulation and Delivery:** Maintaining cell viability during storage and ensuring effective delivery to the root zone remain significant technical challenges (Kumarathilaka et al., 2020).
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Regulatory Gaps: The lack of standardized protocols for the registration and quality control of microbial products hinders commercialization (Meena et al., 2020).

To overcome these hurdles, there is a growing emphasis on using indigenous PGPB isolated from the target environment and developing robust bioformulations, such as talc-based powders or liquid carriers that protect the bacteria during application (Thakur et al., 2024).

9. Conclusions

The intensifying triad of salinity, drought, and heavy metal stresses poses an existential challenge to rice productivity, threatening global food security in a warming world. This review underscores the transformative potential of PGPB as versatile, biologically driven solutions that bypass the limitations of traditional genetic approaches. By orchestrating direct growth promotion through hormonal and nutritional enhancements, ethylene modulation via ACC deaminase, and indirect defenses via ISR and antimicrobial actions, PGPB fortify rice against multifaceted abiotic assaults preserving ion balance, quenching oxidative stress, and minimizing toxin uptake. Empirical evidence from diverse strains (*Bacillus, Pseudomonas*) demonstrates consistent improvements in physiological traits (chlorophyll retention, root proliferation) and agronomic outcomes (15–50% yield boosts), with consortia outperforming single inoculants. Nonetheless, realizing widespread adoption demands overcoming hurdles like inoculum stability, host-strain compatibility, and regulatory frameworks through advanced formulations (biofertilizers) and integrated management. Ultimately, harnessing PGPB not only sustains rice yields in marginal environments but also advances eco-sustainable farming, reducing chemical inputs and supporting resilient agroecosystems essential for feeding future generations.

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