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REVIEW ARTICLE

Sustainable phosphorus management: Leveraging phosphate solubilizing bacteria for enhanced rice growth

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Abstract

Phosphorus (P) is a crucial limiting nutrient in soils, directly impacting plant growth and yield. Its availability to plants is generally low due to high fixation, poor solubility and slow diffusion rates. Over 80 % of the P applied to soil in agricultural systems becomes fixed as insoluble phosphates, with less than 20 % being utilized by crops. This leads to an accumulation of P in the soil. Continuous farming with fertilization contributes significantly to this P buildup. Research on P budgets shows that the amount of insoluble P in soil far exceeds what crops need, suggesting a significant opportunity to reduce inorganic P fertilization by tapping into these native P reserves. However, the natural solubilization of these reserves is minimal. Improving P solubilization could help unlock this unavailable P for plant use. Phosphate-solubilizing bacteria (PSB) have gained prominence due to their potential to reduce the need for P fertilizers, mitigate environmental pollution and boost agricultural productivity. This review explores the diversity of PSB, the mechanisms they use to solubilize native soil P, their effectiveness in various environmental conditions and their impact on crop productivity and P use efficiency, particularly in rice systems.

Keywords

inorganic fertilizer reduction; phosphate solubilization; PSB; P use efficiency; rice

Introduction

Rice is a prime food for a large proportion of the population across the world, especially in tropical and subtropical countries. Global rice production in 2022-23 was about 520 million metric tonnes (1), in which Asian countries alone contributed around 85 to 90 % of the total production. Owing to progressive population growth, the demand for rice by 2035 is forecasted to be 850 million tonnes (2). Hence, to meet the future needs, balanced utilization of nutrient reserves is essential.

Phosphorus is one of the predominant essential elements, next to nitrogen, in influencing the growth and yield of crops. It plays a decisive role in metabolic processes and serves structural, energetic and regulatory functions (3). In rice, P helps maintain membrane integrity, promotes tillering, root growth, early flowering, maturation (particularly in low temperature) and increases straw strength (4). Reduced tillering in low P soil is a common characteristic that leads to a decline in yield (5). Plant maturity becomes delayed under phosphorus-limiting conditions due to poor CO_2 assimilation and reduced transfer of metabolites to the reproductive parts. As a result, rice yield declines to a considerable extent (6), depending upon the intensity of P deficiency and crop genotypes.

The availability of applied phosphorus is very low due to higher fixation and slow diffusion. The P fixing capacity of the soil varies with soil type, texture and the type of clay present in the soil. Clay has a strong affinity for phosphorus, leading to the absorption and fixation of applied P, which renders P unavailable to plant roots. Depending on the soil pH, crops uptake phosphorus in different ortho phosphate forms ($H_2PO_4^-$ or HPO_4^{2-}). Among the soil orders, Entisols have the highest P availability, whereas highly weathered Ultisols have low P availability (7). P availability is lower in clay soils with higher anion exchange capacity, especially in 1:1 type clay. The soluble P reacts with Al^{3+} and Fe^{2+}, precipitating as insoluble phosphates (8) under acidic condition, whereas Ca^{2+} ions cause precipitation in calcareous environments (9). In total, soil P availability to plants is very limited, which is a concern for enhancing crop production.

Crop uptake accounts for about 10 to 30 % of applied P for their metabolic needs (10), while the remaining 70 to 90 % of applied P gets fixed in the soil (11). This leads to an enhancement of total P in soils under prolonged fertilization. The researchers inferred those thirty-three years of continuous fertilization increased the available P content from 2 mg kg^{-1} to 26 mg kg^{-1} between 1981 and 2013 (12). Several studies have shown a significant increase in residual P because of long-term fertilization (13-15).

Excessive P in the soil pool is advantageous as it supplies adequate P to crops while simultaneously reducing the need for P fertilizer usage. Hence, there is significant scope for P fertilizer reduction in the coming days, particularly in systems where continuous P fertilizers are applied. Conversely, surplus P significantly downgrades the availability of zinc and iron (16). Additionally, it poses a threat to environmental health by promoting algal growth (17) and eutrophication of water bodies (18). According to estimates, if the P held in reserve in croplands can be made bioavailable, the requirement for phosphatic fertilizers may be reduced, leading to higher phosphorus use efficiency (19).

Solubilizing fixed P fractions with the aid of phosphate-solubilizing microbes (PSM), such as PSB, phosphate-solubilizing fungi (PSF) and arbuscular mycorrhizal fungi (AMF), improves the P availability to plants, which leads to a reduction in P fertilizer demands for crop needs (20). PSMs engage diverse mechanisms to solubilize insoluble phosphates (21), prolong phosphorus availability through organic P mineralization (22) and support the metabolic activities of crops (23). However, the lack of competitiveness with native microbes and poor rhizospheric adaptations reduce the performance of PSMs under different ecosystems. Conversely, the adaptation of PSMs under lowland conditions is still context-specific; due to the prevailing waterlogged environment, PSF and AMF have failed to flourish vigorously, whereas PSB thrives well under anoxic conditions.

Hence in rice cropping, extensive scopes are available to utilize environment-friendly phosphate solubilizing bacteria to reduce P fertilizer requirement, thereby averting the environmental hazards.

Diversity of PSB

PSMs, commonly referred to as microphos, are diverse and ubiquitous across ecosystems. Over 2286 bacterial, 398 fungal and 20 archaeal strains have been identified as P solubilizers, including 25 bacterial and 5 fungal genera. Notably, around 90 strains can solubilize both inorganic and organic phosphorus, predominantly from genera like *Paenibacillus, Bacillus, Pseudomonas* and *Aspergillus* (24). Among the various organisms, bacteria exhibit diverse P solubilization abilities and adaptability to various conditions (Fig. 1). Well-aerated soils favor microbial phosphate solubilization, with bacterial strains generally being more efficient than fungal strains. In flooded soils, anaerobic bacterial strains such as *Aeromonas* and *Enterobacter* excel, while aerobic conditions favour genera like *Agrobacterium* and *Micrococcus* (25).

In acidic soils, acidophilic PSBs like *Enterobacter* sp. dominate, while alkaline soils are characterized by alkaliphilic *Bacillus* sp. (26, 27). The microbial community at the plant-root interface significantly influences solubilization abilities, with PSBs comprising 1 to 50 % of the rhizospheric population, outnumbering mycorrhizal fungi (28). Inoculation of PSBs has been shown to reduce sheath blight incidence by inhibiting pathogenic fungi (29).

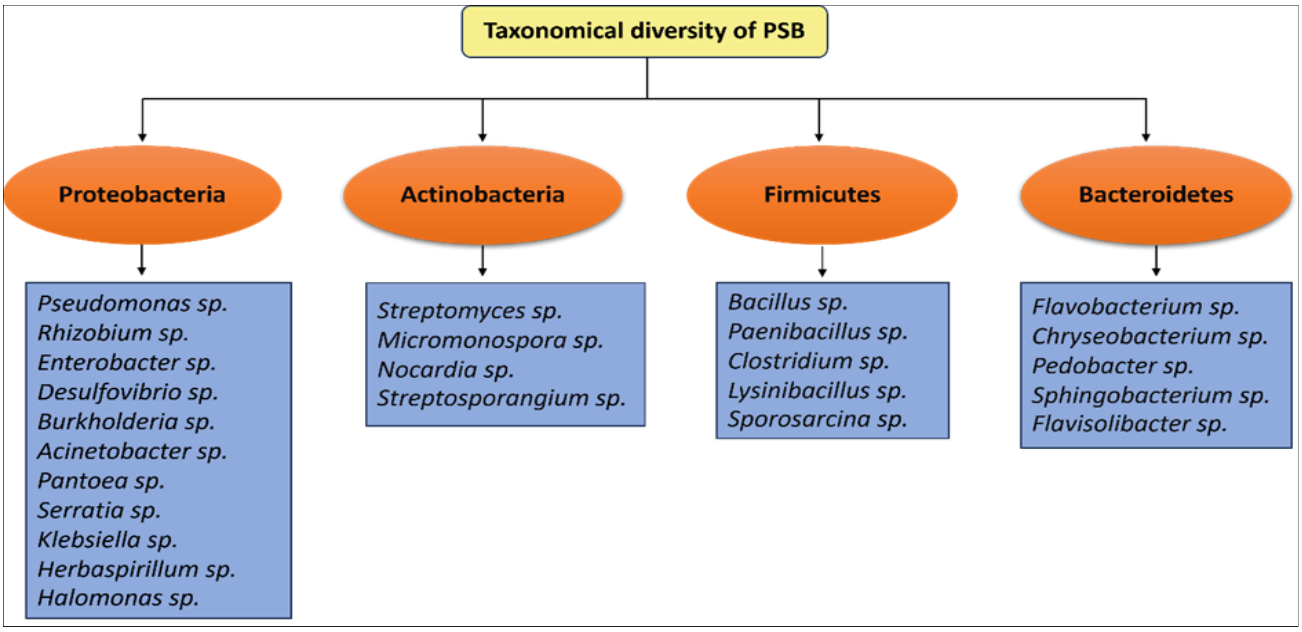

Fig. 1. Taxonomical diversity of phosphate-solubilizing bacteria.

The effectiveness of PSBs in the rhizosphere varies based on soil type, plant species and root exudates. *Pseudomonas* sp. is often more prevalent than *Bacillus* strains, making it a preferred PSB and biocontrol agent. Long-term phosphorus application can reduce the diversity of *Bacillus, Clostridium* and *Alicyclobacillus* in paddy soils (30), while *Burkholderia* sp. thrives under low P conditions.

PSBs promote plant growth by producing hormones like auxin and gibberellins, enhancing nitrogen fixation and solubilizing potassium (31). They also produce gluconic acid, which aids in phosphate solubilization and alleviate plant stress by synthesizing ACC deaminase, reducing ethylene production. Raymond *et al*. (32) noted that PSBs can act as both sources and sinks of phosphorus, with microbial biomass serving as a temporary pool for phosphorus that can be mineralized and released into the soil solution (Fig. 2).

While much research has focused on PSB performance *in vitro*, studies on their *in vivo* conditions remain limited and often yield reduced efficacy. Further exploration is needed to understand the impact of PSB inoculation on soil reserve P availability, as this question is complex and context dependent.

Mechanisms of Phosphate Solubilization

Organic phosphate mineralization

Organic phosphates constitute 30 to 65 % of soil phosphorus (33), increasing with organic matter content. Inositol phosphates (60 % of organic P), nucleic acids and phospholipids are key components. Fulvic acids dominate the organic phosphorus pool, being highly soluble. Organic P sources include plant and animal debris, microbial cells and biomolecules (34).

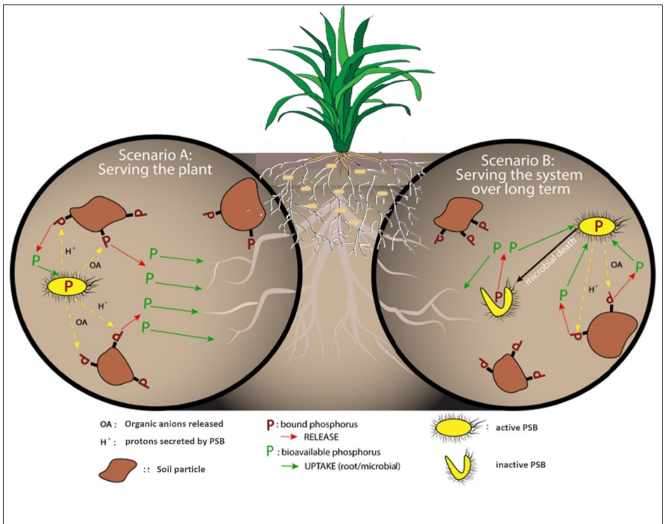

Fig. 2. Role of phosphate-solubilizing bacteria in soil phosphorus cycling (31).

PSB secretes phosphatases, which catalyze organic phosphorus mineralization by breaking down phosphoric acid esters. Acid and alkaline phosphatases operate under different pH conditions, with alkaline phosphatase dephosphorylating approximately 90 % of organic P (35). Class A, B and C phosphatases differ in their localization within the microbial community. Studies highlight their role in enhancing plant root and shoot growth (36). Phytase or Myo-inositol hexakisphosphate phosphohydrolase, dephosphorylates phytic acid, the main organic phosphorus form found in seeds (37). This process improves bioavailability of P and essential metals such as Zn^{2+}, Fe^{2+} and Ca^{2+} (38), thereby aiding plant growth (39). Additionally, phosphonates, complex organophosphates with stable C-P bonds, play a vital role in the phosphorus cycle. Microbes utilize phosphonates as a source of P during periods of scarcity, releasing them as metabolites. Enzymes such as C-P lyase and phosphonatase degrade phosphonates, improving phosphorus availability (40).

Inorganic phosphate solubilization

Inorganic P constitutes 20 to 80 % of total soil P, but much of it remains in occluded forms. PSB release organic acids (citric, oxalic, gluconic) to solubilize these P reserves, lowering soil pH and chelating cations responsible for P precipitation (41).

Soil microbes produce organic acids such as citric, oxalic, gluconic and succinic acids to solubilize P by lowering pH, chelating cations and competing for adsorption sites (Fig. 3). Studies show that PSB can release these acids in varying quantities to enhance P availability (42). Organic anions like oxalic acid are highly effective in solubilizing rock phosphate, while aliphatic and dicarboxylic acids are more efficient than monocarboxylic acids (43).

Siderophores produced by PSB in iron-deficient conditions chelate iron and other metals, aiding in P solubilization and environmental protection. Their efficiency decreases as pH increases, but they remain effective against rice pathogens like *Fusarium* sp. (44). Exopolysaccharides (EPS),

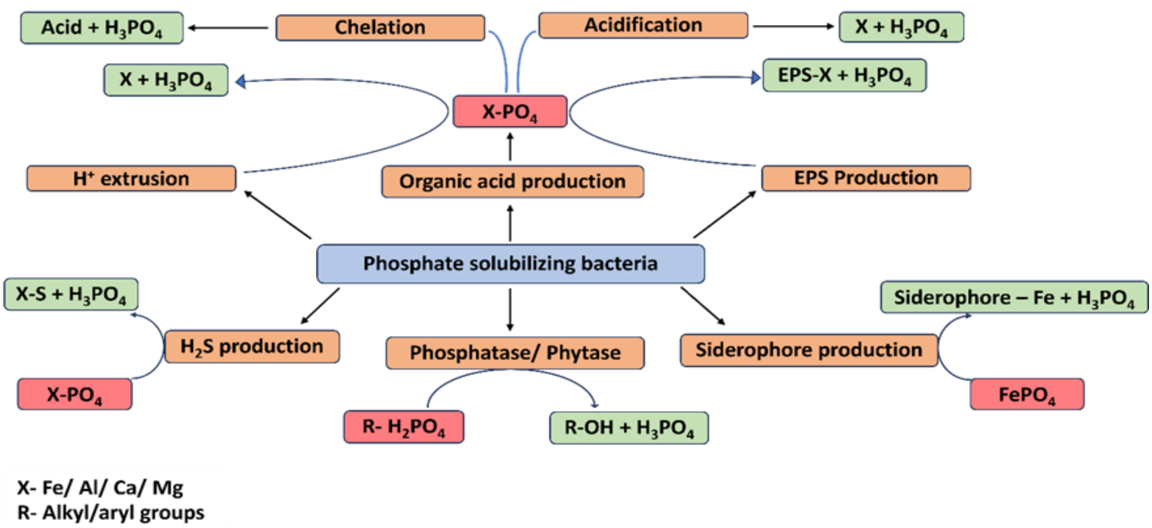

Fig. 3. Phosphate solubilization mechanisms of PSB to release fixed phosphorus.

secreted under stress conditions, indirectly solubilize P by binding metal ions and competing with phosphates. EPS also protects microbes from environmental stress and enhances P availability while contributing to rice plant health under salt stress (45, 46). Previous findings proved that the genes gcd, pqqE and pqqC are involved in glucose dehydrogenase-mediated phosphate solubilization by *Acinetobacter* sp. (MR5) and *Pseudomonas* sp. (MR7), resulting in the promotion of vegetative growth and increased grain production with a 20 % reduction in P fertilization (47). Proton release through NH_4^+ assimilation or respiration is another method of solubilization, lowering soil pH in the absence of acid production. Additionally, H_2S production in anaerobic, waterlogged conditions helps convert ferric phosphate into soluble ferrous sulphate (48). PSB also exhibit biocontrol properties, inhibiting pathogens like *Fusarium, Magnaporthe* and *Rhizoctonia*, making them effective in pest and disease management in rice (49).

Role in fertility management under problem soil

The soil and associated stress conditions have a greater influence on crop growth and soil biodiversity. The major stresses that negatively correlate with crop yield are salinity, metal toxicity and drought. These stresses disrupt optimal plant metabolism by inducing the production of antioxidative enzymes, reactive oxygen species, ethylene and other enzymes. PSB are potential bioremediation agents for abiotic stress factors, as they invoke different mechanisms to reduce the effects of both biotic and abiotic stress in rice.

PSB on salt stress

Globally, around 887 M ha of land are affected by salt stress and it is estimated that 50 % of the croplands will be severely affected by 2050 (50). The increased concentrations of basic cations, carbonates and bicarbonates results in increased osmotic and ionic imbalances in plant cells, interrupting nutrient uptake and optimum metabolic activities, which can cause necrosis of leaf tissues. The remediation or management strategies have been outpaced by the rates of sodication and salinization processes; hence, an alternative strategy is needed that aligns with reduced environmental hazards.

In salt-affected soils, PSB have the capability to thrive well under high saline conditions. The isolation of these microbes can enhance P acquisition in rice by immobilizing basic ions, consequently maintaining osmoregulation (51) (Table 1).

PSB on acid sulphate soils

Acid sulphate soils contain iron sulphide ores in the prolonged waterlogging conditions and upon oxidation, these soils become more acidic. The common constrains in acid sulphate soils are Fe, Al and H_2S toxicity, soil acidity and soil salinity in intertidal zones. The accumulation of Fe, Al and H_2S creates limiting conditions for the rice growth, especially in lowland cultivation. Approximately 12 to 15 M ha of acid sulphate soils are distributed across different regions of the world (60). PSB invoke different mechanisms to scavenge Al^{3+}, Fe^{2+} and Mn^{2+} toxins, paving a biological approach for remediating acid sulphate soils for sustainable crop production. However, studies on PSB in relation to toxins and phosphate solubilization under acid sulphate soils are meager and do not provide concise data (Table 2).

PSB on heavy metal stress

Heavy metals are high molecular weight elements that include essential micronutrients like iron, manganese, molybdenum and copper. The accumulation of heavy metals in soils results in the bioaugmentation and accumulation in the food web, which threatens soil diversity and food security, ultimately impacting human health. In the plant cycle, buildup of heavy metals disrupts protein synthesis and chlorophyll content by replacing Mg ions and leads to the breakdown of carotenoids. Although phytoremediation is a viable option, it is impeded by long growth cycles, depth limitations and challenges

Table 1. Mechanisms of soil stress reduction through phosphate-solubilizing bacteria

PSB	Plant growth promoting properties	Mode of action to alleviate salt stress	Reference
Bacillus pumilus strain JPVS11	IAA, ACC deaminase activities, ammonia, HCN, siderophore and EPS production	Reduction in ethylene levels and Na^+ uptake, immobilization of ions, biofilm formation aggregate formation, increased concentration of antioxidative enzymes like catalase and super oxide dismutase and population of other microbial communities	(52)
Bacillus aryabhattai, *Achromobacter denitrificans* and *Ochrobactrum intermedium*	Gibberellin, indoleacetic acid, ACC deaminase, extracellular phytase, chitinase and antifungal peptides	Biofilm formation, proline accumulation, increase in total protein and carbohydrate contents and overexpression of salt tolerant genes (BZ8, SOS1,	(53)
Pseudomonas sp. K32 strain	IAA, N_2 fixation, PS and EPS production	Metal chelation, increased catalase activity of rice seedlings	(54)
Bacillus atrophaeus GQJK17 S8	EPS, IAA, N_2 fixation and PS	Biofilm formation, enhanced catalase, peroxidase, super oxide dismutase, proline and TSS production (osmoprotectants). Increased	(55)
Bacillus sp. strain PnD	IAA, siderophore, PS and ACC deaminase	Seed priming of isolate improved photosynthetic pigments, nitrogen uptake and biomass production	(56)
Pseudomonas stutzeri and *Klebsiella pneumonia*	IAA, NH_3, N_2 fixation, P solubilization, siderophore and ACC deaminase production	Regulation of intracellular ionic concentration (Na^+ and K^+) by osmotic adaptations	(57)
Alcaligens sp., *Bacillus* sp. and *Ochrobactrum* sp.	IAA, siderophore, ACC deaminase, ammonia and phosphate solubilizing activity	Ethylene reduction and amylase production	(58)
Pantoea agglomerans strain KL	Production of IAA, siderophore, nitrogen fixation, EPS and phosphate solubilization	Reduced ethylene stress, increased Ca^{2+} and K^+ uptake by reduced Na^+ influx	(59)

Table 2. Mechanisms of acid sulphate soils through phosphate-solubilizing bacteria

PSB	Plant growth promoting properties	Mode of action	Reference
Rhodopseudomonas palustris strains TLS12, VNS19, VNS32, VNS62 and *VNW95* and *Rhodopseudomonas harwoodiae* strain TLW42	Production of (EPS), siderophores, 5-aminolevulinic acid (ALA) and IAA	Biosorption and bioaccumulation of Mn^{2+}	(61)
Rhodopseudomonas sp.	Production of NH_4^+, siderophores, IAA and ALA	Biosorption leads to decrease in concentrations of toxins Al^{3+} by 12.1% - 19.7 % and Fe^{2+} by 16.6 % - 19.0 %.	(62)
Luteovulum sphaeroides	EPS, IAA, siderophore and ALA	H^+, Al^{3+}, Fe^{2+} and Mn^{2+} reduction under rice - shrimp ecosystem by forming biofilm	(63)
Rhodopseudomonas pentothenatexigens	EPS, IAA, siderophore, PS, Zn solubilization and GA	Al^{3+}, Fe^{2+} and Mn^{2+} toxicity by siderophore complex	(64)
Bacillus sp., *Stenotrophomonas maltophila, Burkholderia thailandensis* and *Burkholderia seminalis*	Organic acids, EPS, IAA and siderophores	Chelation and immobilization of Al^{3+}	(65)

associated with plant biomass disposal, making broad-scale use complex. Therefore, shifting towards microbial approaches to reduce the metal poisoning such as biosorption, biotransformation, bioaccumulation, bioleaching and detoxification represents a promising strategy (Fig. 4) (Table 3).

PSB on drought stress

Agricultural drought is a condition characterized by a soil water deficit that affects crop growth. Drought reduces cell turgor, increases cell potential through the accumulation of solutes and leads to wilting of crops. PSB under drought conditions produce abscisic acid (ABA), which results in the closure of stomata, thereby reducing gas exchange and transpiration. Additionally, the production of ACC deaminase helps scavenge ROS, mitigating drought stress and decreasing ethylene production (68) (Table 4).

PSB in wetlands

Submergence increases P solubilization due to reduced conditions but decreases over time due to re-precipitation of ions. Organic acids and higher CO_2 levels in anaerobic conditions enhance P availability by forming carbonic acid. Continuous use of superphosphate or DAP raises soil pH through Ca buildup from dissolving tricalcium phosphate. Under submerged conditions, P fractions follow the order: Ca-P > Fe-P > Al-P > RS-P > Saloid-P, though Fe-P and RS-P dominate in acidic soils.

Table 3. Mechanisms of heavy metal stress through phosphate-solubilizing bacteria

PSB	Plant growth promoting properties	Mode of action to alleviate heavy metal stress	Reference
Halomonas sp. Exo1	EPS, IAA, NH_3, N_2 fixation, siderophore, PS and HCN	Biosorption of As	(66)
Bacillus aryabhattai, Achromobacter denitrificans and *Ochrobactrum intermedium*	Gibberellin, indoleacetic acid, ACC deaminase, extracellular phytase, chitinase and antifungal peptides	Immobilization of Ni and Cu	(53)
Pseudomonas sp. K32 strain	IAA, N_2 fixation, PS and EPS production	Reduced Cd uptake also able to tolerate Pb and As stress	(54)
Bacillus licheniformis NCCP-59	Gibberellin and amylase production	Reduced uptake of basic cations and Ni stress by enhancing phytoremediation	(67)

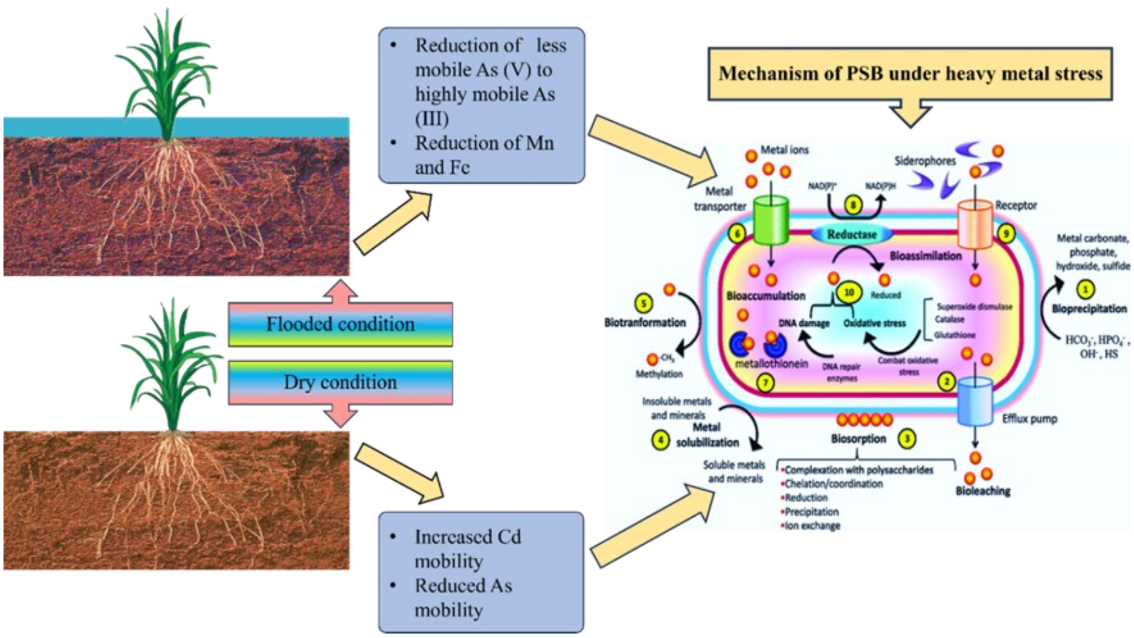

Fig. 4. Mechanism of PSB under heavy metal stress.

Table 4. Mechanisms of drought stress through phosphate-solubilizing bacteria

PSB	PGP produced	Drought resistance	Reference
Bacillus subtilis NM-2, *Brucella haematophilum* NM-4 and *Bacillus cereus* NM-6	ACC deaminase activity, exopolysaccharide production, phosphate P solubilizing activity, IAA, production of organic acids	Water stress mitigation by the synthesis of proline, antioxidant enzymes and enhanced cellular water content	(69)
Bacillus megaterium PB50	IAA production, GA production, ACC deaminase activity and exopolysaccharide production	Seed inoculation and foliar spray of isolate enhances the drought tolerance capacity by increasing proline, ABA and phenolic	(70)
Bacillus and *Enterobacter* sp.	EPS, IAA production, P solubilization, ammonia production, siderophore, ACC deaminase activity, HCN production and N_2	Enhanced water retention capacity by biofilm and reduced ethylene production with higher anti pathogenic behaviour	(71)
Bacillus pumilus SH-9	EPS, siderophore, ACC deaminase, ABA and sucrose production, P solubilization	Seed biopriming of the isolate reduce redox stress and enhanced seed germination	(72)

SOD - superoxide dismutase; POD - peroxidase; CAT - catalase, HCN - Hydrogen cyanide; IAA – indole acetic acid; APX - Ascorbate peroxidase; ACC deaminase - 1-aminocyclopropane-1-carboxylate deaminase

Adding PSB strains like *Acinetobacter* sp. MR5 and *Pseudomonas* sp. MR7 can reduce P fertilization by 20% and suppress BLB disease by 56 % (46). The integration of *Burkholderia* spp. with P fertilizer increased dry matter (13.27 %), panicles (37.68 %), grain yield (29.44 %) and straw yield (50 %) (73). Inoculation with *Pseudomonas putida* and *P. chorii* boosted P solubilization and enhanced disease resistance through siderophores, salicylic acid, HCN and IAA production (74).

PSB in aerobic rice cultivation

The availability of P is negatively correlated with upland conditions, primarily due to reduced hydrolysis and restricted diffusion, which result in decreased plant P acquisition. Upland soils are often highly weathered and exhibit toxicities from Fe, Al and Mn, further limiting P supply. Consequently, P use efficiency is 7 to 8 % lower in upland soils compared to flooded rice soils (75).

The previous research demonstrated that combining PSB with P fertilizer in upland rice enhanced P solubilization capacity: *Bacillus licheniformis* (688.18 µg mL^{-1}), *Pantoea dispersa* (570.90 µg mL^{-1}) and *Staphylococcus* sp. (551.81 µg mL^{-1}), while reducing fertilizer reliance by 50 % (48). Utilizing *Serratia* spp. BRM 32114 in no-tillage aerobic rice increased biomass by 13 %, leaf cation levels, panicle numbers by 11 % and grain yield by 19 % (76). Indigenous PSB strains, such as *Bacillus* sp. PSB9 and PSB16, improved grain yield, plant height, root architecture and P acquisition compared to uninoculated controls (77). Substituting *Acinetobacter baumannii* strain CR 1.8 and *Bacillus subtilis* strain MC 21 also enhanced plant height, root length, root density and dry root weight under aerobic conditions (78).

Methods of application

To optimize phosphorus utilization in crops, it is essential to implement efficient application methods that consider formulation types, crop stages and field conditions. Seed treatment with PSB using adhesives before sowing, integrating them into growth media or nursery bed soils and immersing seedling roots in bioinoculant solutions before transplanting are effective techniques (79). These approaches minimize the impacts of soil heterogeneity and climatic variability on bacterial multiplication. In addition, applying bioinoculants to the main field after a specific inoculation and incubation period in organic matter enhances microbial colonization in both the plant rhizosphere and non-rhizospheric soil. This process improves phosphorus accessibility through diverse mechanisms. Adopting these strategies can significantly boost phosphorus efficiency and crop productivity.

Factors affecting PSB activity

The competence of PSB in the soil-plant continuum depends on various factors. The presence of larger quantities of $CaCO_3$ results in an increase in soil pH and reduced P solubilization, as it affects the growth of a major diversity of PSB and leads to the reprecipitation of the solubilized phosphates. P solubilization capacity is negatively correlated with salt concentrations, as high salt levels delay the proliferation of microbes and lead to neutralization of released protons due to higher sodium and chloride concentrations (80). Aeration increases P solubilization capacity compared to anoxic conditions. Di and Tri calcium phosphates have greater solubilization capacity than other phosphates. The finer the substrate, the lesser the P solubilization; thus, solubilization capacity increases with coarse and more amorphous sources used. An increased C:P ratio affects the mineralization of organic P. At the ratio of <200:1, net mineralization occurs, while at >300:1, immobilization occurs due to heavy P demand among PSB (81). The incubation period plays a major role in determining organic acid production, which in turn influences P solubilization capacity. Therefore, P solubilization increases with an increase in the incubation period until the nutrients are exhausted, after which it decreases. The genera *Pseudomonas* and *Bacillus* exhibit the highest P solubilization ability (19), while *Streptomyces* shows the least.

Future thrusts

Enhancing the efficiency of phosphate solubilization by exploring genetically modified strains of PSB suitable for specific environmental conditions such as salinity, drought, heavy metals, disease tolerance and waterlogging is essential for customizing component in climate-smart agriculture. Field-level studies are needed to assess the efficiency of PSB on a broad scale rather than relying solely on *in vitro* studies. This will help evaluate the efficacy of PSB across different agroecosystems and crops, as well as their impact on crop crop yield, nutrient uptake, soil health and environmental sustainability under diverse soil and climatic conditions. To advance our understanding of host-PSB interactions, in-depth research is imperative to elucidate signalling pathways, solubilization mechanisms and disease suppression capabilities. Standardizing the production and commercialization of biofertilizers, along with the dissemination of this technology to farmers through extension activities, is vital for fully harnessing the potential of PSB. Studies on the combined usage of enriched rock phosphate in high P soils with PSB represent an initiative to reduce energy wastage and huge capital required for manufacturing phosphatic fertilizers.

Conclusion

A major challenge in modern agriculture is the depletion of phosphorus reserves and the growing need for P fertilizers to meet global food demands. On the other hand, applied P fertilizer is unutilized and accumulating in soil as an insoluble fraction. Phosphorus solubilizing microbes have enormous potential in reducing P fertilizer usage as they transform the insoluble P into soluble P fractions. PSB plays multiple roles in rhizosphere, *viz*., reducing salt stress, scavenging heavy metals, mitigating drought, acting as a growth stimulant and enhancing plant resistance against pathogens. In this way, PSB influences the global economy, food security and ecological well-being. The impact of PSB on rice growth, yield and quality improvement is well acknowledged. Still many more researchable issues are untouched towards improving phosphorus use efficiency. Efficiency of PSB under diverse soil conditions is not yet available. Information on different strains of PSB and their interaction with other microbes in natural habitats is lacking. Rhizosphere interaction of PSB is another unexplored area in microbial science. Hope the agricultural scientists will bridge the gap above issues in the coming days with the advancement of scientific knowledge.

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Authors' contributions

AS and MK conceived the idea and wrote the manuscript. MK gave ideas and AS designed the diagrams and tables. ST revised the manuscript. MK, ES and MS finalized the manuscript. All authors read and approved the final manuscript

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While preparing this work, the authors used Grammarly to improve the language and readability. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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