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Review

Ecological and sustainable implications of phosphorous-solubilizing microorganisms in soil

Anwaar Iftikhar[1] · Rida Farooq[1] · Mubeen Akhtar[1] · Haleema Khalid[1] · Nazim Hussain[1] · Qurban Ali[2] · Saif ul Malook[3] · Daoud Ali[4]

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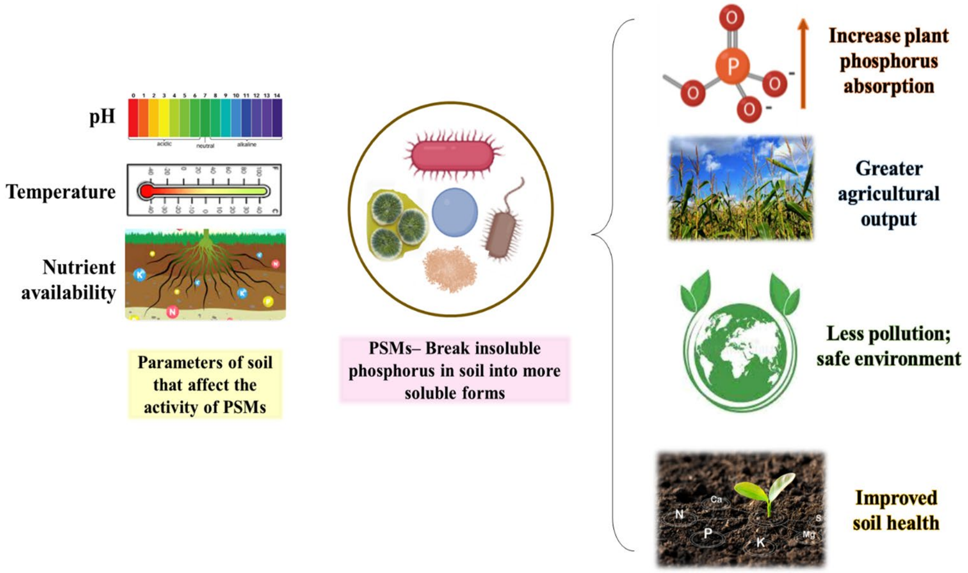
Abstract

Phosphorus (P) is a macronutrient that plants need to grow. However, most of the soil's phosphorus is still insoluble, making it difficult for plants to absorb. This creates a barrier to ecologically responsible farming methods and calls for innovative approaches to phosphorus solubilization. Solublizing microorganisms improve the availability of phosphorous in soil. The term "phosphorus-solubilizing microorganisms" (PSMs) describes various fungi or bacteria that divide the phosphorus into more soluble forms. It shows how PSMs interact with plants and their processes to solubilize phosphorus. Soil pH, temperature, and nutrient availability are only a few parameters affecting its activity. PSMs are investigated for their potential to increase plant phosphorus absorption and use, thereby boosting agricultural yield and nutrient usage efficiency. The use of PSMs and their effects on the environment are also evaluated. By using PSMs, farmers may use less chemical phosphorus fertilizers that contribute to runoff and eutrophication in waterways. Furthermore, PSMs may improve soil structure, decrease nutrient losses, and increase nutrient cycling, all of which contribute to soil health and the long-term viability of agricultural systems. Phosphorus-solubilizing microorganisms have enormous promise in environmentally responsible farming and land management. Better phosphorus availability, greater agricultural output, less pollution, and better soil health are all possible outcomes of using PSMs. However, further study is required to determine the best application strategies, formulations, and choices of PSMs for various soil and plant systems. Incorporating PSMs into agricultural operations can potentially improve environmental sustainability and resilience. This article will explore the potential of PSMs in addressing critical environmental challenges, including soil erosion, nutrient runoff, sustainable farming practices, and resource conservation.

✉ Nazim Hussain, nazim.cam@pu.edu.pk; ✉ Qurban Ali, saim1692@gmail.com; Anwaar Iftikhar, anwaariftikhar33@gmail.com; Rida Farooq, ridafarooq814@gmail.com; Mubeen Akhtar, mubee.botanist@gmail.com; Haleema Khalid, Haleemakhalid347@gmail.com; Saif ul Malook, saifulmalookfnu@uf.edu; Daoud Ali, Aalidaoud@ksu.edu.sa | [1]Centre for Applied Molecular Biology, University of Punjab, Quaid-E-Azam Campus, Lahore, Pakistan. [2]Department of Plant Breeding and Genetics, Faculty of Agricultural Sciences, University of the Punjab, Lahore, Pakistan. [3]Department of Entomology & Nematology, University of Florida, Gainesville, USA. [4]Department of Zoology, College of Science, King Saud University, 11451 Riyadh, Saudi Arabia.

Graphical Abstract



Article Highlights

- The potential of phosphorus-solubilizing microorganisms (PSMs) to address important environmental issues about soil fertility and agricultural practices is examined in this article. A vital macronutrient for plant growth, phosphorus is frequently found in soil in insoluble forms, restricting the amount of phosphorus that plants may access. PSMs, which comprise a variety of bacteria and fungi, are essential in solubilizing phosphorus and increasing its availability to plants. Discussed are the relationships that PSMs have with plants and the variables that affect PSM activity, such as temperature, nutrient availability, and pH of the soil.
- The potential of PSMs to increase plant phosphorus uptake, boost agricultural productivity, and improve nutrient utilization efficiency is highlighted in the study. PSMs provide a more ecologically friendly option to chemical phosphorus fertilizers by decreasing river runoff and eutrophication. The paper also discusses the possible advantages of PSMs, which include better soil structure, less nutrient losses, and increased nutrient cycling, all of which support the sustainability of agricultural systems and general soil health.
- Although the article notes that the results have been encouraging, it also acknowledges that further research is required to determine the best ways to apply, formulate, and select plant soil amendments (PSMs) appropriate for different plant and soil systems. PSM integration is considered a viable path toward environmental resilience and sustainability, successfully tackling issues like resource conservation, nutrient runoff, and soil erosion.

Keywords Phosphorous solubilization · Phosphorous solubilizing microorganisms · Sustainable environment · Biofertilizers · Plant growth promoters · Phosphate · Soil ecology · Agriculture · Agrofarming

Abbreviations

PSMs	Phosphorus solublizing microorganisms
PSB	Phosphate solublizing bacteria
PSF	Phosphorus solublizing fungi
P	Phosphate or phosphorus

1 Introduction

Phosphorus is an essential component for the growth and maturation of plant life, as more than 90% of all phosphorous minerals are utilized in fertilizers nowadays [1]. Their implementation is crucial to mitigate their negative influence, as the microbiological processes or chemical goods design remove or minimize the manufacturing of dangerous compounds or copious waste materials [2] Phosphorus plays an important role in signal transduction, division of cells, membrane stability, and energy production, among other metabolic activities, making it crucial for plant macronutrients. It's also important for plant respiration and nitrogen fixation in legumes [3]). Another possibility is to use microorganisms to transform these agro-industrial byproducts into useful feed additives and bio-industrial goods. Top soil typically contains phosphorus (50 to 3000 mg kg); its availability to plants is only 0.1%. Instead of using costly and energy-intensive chemical methods, a biological method was presented for extracting phosphate from plants [4] PSMs are a viable alternative to agrochemicals because they convert an insoluble form of phosphorus into a soluble form, so a small quantity of phosphate fertilizers is needed. Prior studies of soil microorganisms often focused on only one important function [5] Over the previous 15 years, studies indicated that solubilizing microorganisms might perform additional activities in fermentation, soil conditions, and agricultural land input. Phosphate solubilizing microorganisms increased the 22% supply of wheat grain or 26% phosphorus absorption when combined with phosphate fertilizer while decreasing 30% of fertilizer input [6] An enzyme (ACC deaminase) secreted by several PSMs mitigates ethylene stress in plants. The microscope creatures maintain the best agriculture policy, harmless food, or ecological equilibrium. Phosphorus dynamics in soil have dramatically shifted due to technological advances in agriculture and population pressure. Phosphorus is a deficiency in 67% of the world's farmland [7] Soil microorganisms may alter agricultural yields in response to changing environmental circumstances. Additionally, the efficacy of microorganisms is significantly impacted by climate change. Co-inoculation is a method for improving the performance of microorganisms in challenging environments [8] The addition of chemical phosphate fertilizers is unlikely to boost plant production due to projected limited advancement in plant growth efficiency resulting from their use. The acquisition and/or use of Phosphorus is essential for continued metabolism and development. In comparison, soils often contain little more than a tenth to a quarter as much phosphorus as nitrogen and a twentieth as much potassium [9] Soil phosphorus levels range from roughly 200 to 2000 kg P/ha in the top 15 centimeters of soil, on the order of 1000 kilograms on average. There is insufficient phosphorus on the planet's 5.7 billion hectares to support optimum agricultural production. Soil microorganisms have positive and negative effects on soil health [10] Soil processes such as organic matter decomposition, nitrogen fixation, mineralization or mobilization, denitrification, or sulfur reduction are all mediated by rhizospheric microorganisms [11] Phosphate solubilizing bacteria not only provide phosphorus to plants but also enhance the availability or nitrogen fixation effectiveness of trace elements to stimulate the development of plants. It has been suggested that the effect of weather change on the global P cycle, with repercussions for terrestrial and aquatic ecosystems, disruption of humans, or biological activities, greater the concentration of phosphorus [12] Soil phosphorus geochemical balances and ecosystem processes have been severely disrupted due to human activities such as creating and using organophosphorus compounds [13] These microbes control the agroecosystems' cycling of biogeochemical phosphorus or transform the insoluble form of organic phosphorous or inorganic phosphorous into the soluble form of phosphorus. Numerous heterotrophic and autotrophic microorganisms are dispersed chaotically within the soil microbiome[14]). The three major populations of Phosphate-solubilizing bacteria in soil are the *Bacillus genus, Pseudomonas spp. genus, Pseudomonas sp. species.* By affixing Pi minerals to expand the contact surface in liquid media, Phosphorous phosphorous-solubilizing fungi have superior inorganic phosphorous solubilizing powers over Phosphate Solubilizing Bacteria [15] *Rhizophagus irregularis , Glomus aggregatum, and Glomus mosseae* are all examples of arbuscular mycorrhizal fungus (AMF) capable of solubilizing inorganic phosphorous. Inorganic Phosphate-solubilizing autotrophic bacteria are also known to exist. Different PSMs secrete various organic or inorganic acids, which release the hydrogen ions or reduce the pH medium; therefore, insoluble inorganic phosphate is converted into soluble orthophosphate forms [16] The excretion of organic acid impacts the existence and activity of phosphate solubilizing microorganisms (PSMs) available to soil organisms by chelating Fe and Al ions, making P available to the soil environment. Soil absorption and inorganic Phosphorus solubilization may be improved by using various organic acids or competing with the adsorption sites of phosphorus [17] More efficient phosphorous usage for agricultural uses necessitates further study to create novel methods, explore new agricultural products, and improve methods for administration. This article discusses the significance of phosphorus and its primary sources in agriculture, the potential of phosphorus-solubilizing microorganisms in the solubilization process and usage, and how soil microorganisms affect phosphorus availability and microbial processes. The focus is on how microorganisms can promote vegetable growth and make the insoluble part of phosphorus bioavailable to plants. This paper provides a literature evaluation of studies on phosphate-soluble microorganisms.

2 Occurrence of phosphate solubilizing microbes

Various microorganisms like archaea, fungi, or bacteria were suggested to dissolve insoluble P [18] Soil bacteria (1 to 50%) or soil fungi (0.1 to 0.5%) can solubilize phosphorus. The soil is a thriving community of microorganisms. Phosphate Solubilizing Microorganisms (PSMSs) are distinguished by their ability to produce the 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase enzyme. Some Phosphate solubilizing microorganisms (PSMs) can produce 1 aminocyclopropane 1 carboxylic acid (ACC) deaminase enzyme, depending on their particular bacterial strain or gene, lowering ethylene levels in plants subjected to stress [19]. Under stressful situations, plants release more ethylene than usual (big peak) > 25 g L^{-1}, which slows their development [20] ACC is transformed into -ketobutyrate or ammonia, in which deamination of ACC helps plants survive or thrive in adverse environments by reducing ethylene production. *Bacillus subtilis strains 1, 2 or 3, Pseudomonas aeruginosa* were determined using 16S rRNA. These strains fare best when cultivated and exposed to stressors, and the pH level is either 6.8 or 8.8, the temperature is 28 or 37 °C, or the salt level is 1 or 2% [21] The results showed that the efficiency of phosphate solubilizing ranged from 35 to 50, with *B. subtilis strain 3*, having the highest efficiency (10.22 g ml^{-1}). Phosphate mines were the source of the fungi *Candida krissii, Penicillium expansum, or Mucor ramosissimus* that made up the Phosphate Solubilizing Fungi. Phosphate solubilization is the only phosphate supply, so it varied in different growth mediums with rock phosphate [22] Insoluble phosphorus may be converted into a form that plants can use by PSMSs. It is richly present in soil or can be used to check the capability of phosphorus solubilization. Although creating halo zones on a solid agar medium is one way to evaluate a microbe's Phosphorous-solubilizing ability, many other, more accurate tests may be conducted in liquid media [23] Soybean rhizosphere isolates, the *Pseudomonas plecoglossicida*, is one such unique elite strain; it has been shown to solubilize phosphorus or to create the hormones for the growth of plants like indole acetic acid. In very salty circumstances, namely at a 1.5 M NaCl concentration, it has been shown that *Gordonia terrae* solubilized 299 mg L^{-1} phosphorus [24] Phosphorus up to 288.18 g mL^{-1} is solubilized by *Trichoderma harzianum*. The indole acetic acid production by the strain was 21.14 g mL.$^{-1}$. Fungi treatment of *Solanum lycopersicum L.* plants resulted in increased biomass of root or shoot, leaf number, or area compared to uninoculated plants [25] Also, certain isolates might be tested for their ability to generate various organic acids in a liquid medium. Isolates meeting the above mentioned criteria should then undergo a final confirmation test on a model plant to determine whether they can solubilize P [17]. Soil samples were gathered from all over the world that had previously been used for farming purposes, namely the cultivation of vegetables, grains, and legumes. Solubilizing bacterial populations ranged from 25,103 to 550,103 Colony Forming Units per gram of soil, whereas the population of fungus ranged from 2.0103 to 5.0103 Colony Forming Units per gram of soil[26]). Mycorrhizal fungi include *Entrophospora colombiana, Rhizophagus irregularis, Glomus fasciculatum, or Glomus mosseae.* The purposes of PSMs are wide-ranging. In addition to aiding plant development, they are renowned for their ability to generate chemicals, which is growth-promoting [27] Different hormones of plant growth, like auxin, gibberellins, abscisic acid, have been reported for secreting by the novel strain *Bacillus tequilensis*, or its soybean inculcation was improving photosynthesis pigment, shoot biomass, or leaf ultrastructure during heat stress [28] The rhizosphere showed a decrease in stress abscisic acid and an increase in jasmonic acid and salicylic acid. *Bacillus, Pseudomonas* species*, Penicillium, or Aspergillus* are the most often isolated bacteria and fungi, respectively, by culture techniques [29] The capability of these organisms in mineral phosphate solubilizing or density varies from production to production or from soil to soil. Figure 1 *shows the occurrence of various Phosphorous Solubilizing Microorganisms.* Common isolation methods include culture or dilution techniques, which may be used on soils from the rhizosphere, no rhizosphere, rhizoplane, phyllo sphere, rock P deposit region, and stressed environments [30]

3 Molecular mechanisms of phosphorus solubilization

The most significant effects on phosphorus concentrations are caused by dissolution, precipitation, sorption, and desorption. The substrate is mineralized with the help of secreted enzymes, acidic substances, protons, and siderophores [31] Additionally, the Phosphorous Solubilizing Microorganisms provide many pathways for phosphate solubilization.

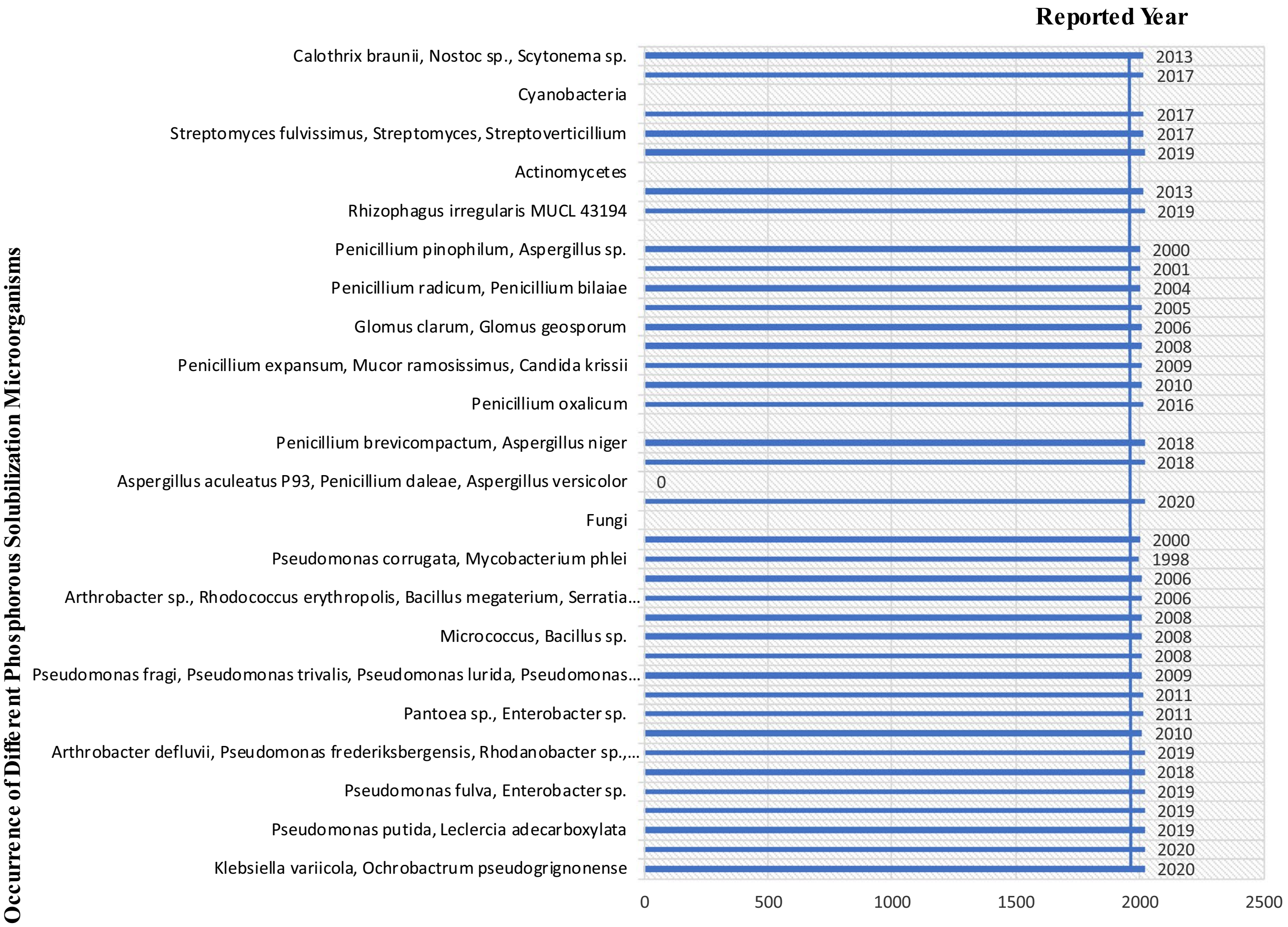


Fig. 1 shows the presence of various Phosphorus Solubilizing Microorganisms Like bacteria, and Fungi in different reported years (30, 31, 32)

3.1 Organic acid, proton, and siderophore secretion

Organic acids that are released by PSMSs, such as citric acid, gluconic acid, oxalic acid, and tartaric acid, help dissolve inorganic phosphates by competing with phosphate for an adsorbent site, binding anions, lowering pH, and interacting with metal ions [32] The gcd gene encodes a glucose dehydrogenase enzyme, which requires a cofactor called pyrroloquinoline quinone (PQQ) to function properly. *Rahnella aquatilis* HX2 with a pqqA gene mutation had far less gluconic acid and available phosphorus [33] Phosphorus-solubilizing *Pseudomonas*sp. strain AZ15 was capable of solubilizing phosphorus at concentrations of up to 109.4 g mL $^{-1}$ linked to the production of oxalic acid, gluconic acid, acetic acid, lactic acid, and citric acid. Phosphorus-solubilizing as the primary route of phosphorus solubilization in soybean, organic acids generated by several *Trichoderma* strains increased plant growth by anywhere from 2.1% to 41.4 percent [34] One gram per liter (g/L) of elemental sulfur was converted to 203 mg/L (mg/L) sulfate by the sulfur-oxidizing bacteriumDelftia sp. strain SR4, while 20 mM thiosulfate was converted to 220 mg/L (mg/L) sulfate by the same bacteria. This variety showed significant (up to 116%) efficiency of phosphorus solubilization in infected *Brassica juncea* plants compared to control plants [35] The bioavailability of nutrients in plants is affected by microorganisms in a wide variety of ways. For instance, mycorrhizal fungi may extend the root surface by multiplying their mycelium, which aids in nutrient exploitation by allowing the plant to reach soil parts (such as microaggregates) that would otherwise be inaccessible [36] Hydrogen sulphide, produced by acidophilic and sulfur-oxidizing bacteria, interacts with ferric phosphate to make ferrous sulphate, liberating bound phosphorus [37] *Delftia*sp. *strain SR4* exhibited up to 116% greater efficiency in inoculation plants of *Brassica juncea,* oxidizing 1 g L^{-1}elemental sulphur to 203 mg L^{-1} sulphate and 20 mM thiosulfate to 220 mg $L.^{-1}$ sulphate [38] Microorganisms may also dissolve phosphorus in soil via a process called proton extrusion. A Pseudomonas sp. culture filtrate analysis discovered phosphorus dissolution activity but no organic acid generation. By releasing an excess proton H + from the cytoplasm of the microbial cell [39] Conversion of soil ammonium (NH4 +) to ammonia (NH3) helps dissolve insoluble phosphorus by acidifying the bacterial cell's environment. Despite its low molecular weight, siderophores are a secondary metabolite generated by PSMs that acts as a metal chelator and has a high affinity for inorganic iron[40]). At neutral to alkaline pH, they function to liberate the Phosphorous-bound metal and make it available to plants. *Streptomyces*sp. *CoT10* was shown to help in Iron bounded Phosphate mobilization, increasing Phosphate availability by 15%, and release of 72.49 mg/L for FePO4, which was notable in the formation of various siderophores and the capacity of *Streptomyces* sp [41] Pi acquisition by chelation and ligand exchange is considerably accelerated by carboxylate exudation, such as citrate, malate, and oxalate. The effects of anion channel blockers provide evidence that anion channels are involved in the excretion of organic acids. Malate exudation is discovered to be mediated by the Al-activated malate transporter, and multicellular plants may produce phosphatase to mobilize Po by enzyme-catalyzed hydrolysis. *CoT10* endophytic activity of *Camellia oleifera* to mobilize Phosphorous in acidic and deficient soils. Plants use photosynthetic substrates to increase root growth capacity and scavenge soil Phosphate [41]

3.2 Phosphorus mineralization

Phosphorus is divided into two main forms is divided into two main forms (1) organic form, in which carbon atoms are covalently attached to other elements (2) inorganic form, which includes organic matter, minerals bound, orthophosphate anions, or mineral adsorption surface and is found in environments such as water and soil[42]). The substrate's conversion to choline catalyzes the enzyme, releasing P. Forty to eighty percent of the phosphorus in soil is organic. When a lack of phosphorus stresses plants, they release more enzymes capable of breaking down phosphorus[43, 44]). Additionally, phosphates may be dissolved. Soil phosphatase enzyme processes are very significant because organic acids influence them. Soil phosphatases are crucial to mineralizing organic phosphorus (P) [45] PSMs secrete phosphatases, which facilitate the natural phosphorus mineralization. Orthophosphates from organic phosphorus soil are liberated by phosphatases produced by microorganisms, which are coupled with phosphate compounds rather than plants [46] Non-specific serine proteases (NSAPs) are a group of enzymes found in microbial lipoprotein membranes or released extracellularly. Phosphomonoesters (PMEs) are enzymes that function at the ideal pH of their surroundings, which may be either acidic or alkaline [47] Approximately 90% of organic phosphates in soil enzymes were dephosphorylating a broad range of phosphoesters. Most organic P in soil is found as nucleic acid, phytic acid, and many organic residues Phytate, an organic form of phosphorus, contains greater than half the quantity of phosphorus in soil (inositol hex phosphate) [48] However, they are not easily accessible for plant absorption due to their complicated formation with cations or their adsorption on various soil organic components [49] In some cases, plants show symbiotic relationships with fungi to exchange nutrients. So, the plant is divided into two halves; one is attached to roots, and the second is with hyphae, which completed the tested fungi to various calcium phytate absorptions and both inoculated and uninoculated maize (*Zea mays*) cultivars [50] Phosphatases (phosphonate hydrolases) are enzymes that catalyze the breakdown of this link between nutrients using a group -carbonyl electron scavenger. In addition to phosphoenolpyruvate and phosphonoacetate, phosphoenol-acetaldehyde can work as a phosphonate substrate [51] Apatite P may be dissolved by various bacterial strains belonging to the genus *Thiobacillus*. First, *T. thioparus ATCC 23645* was utilized alone; second, *T. thioparus C5* was mixed with *T. thioparus ATCC 8085*. Approximately 1, 10, and 20% (P/V) of apatite were present in the Apatite sulfur culture medium (ASM), which was used to confirm the phosphate solubilization capability and is related through a sequence of geological and chemical processes [52] *Kushneria*sp. *YCWA18's* capacity for P solubilization in two culture mediums with different concentrations of P sources (calcium phosphate Ca3 (PO4)2 and lecithin. The pH of the Ca3 (PO4)2 medium changed from 7.21 to 4.24 throughout 11 days of culture, and the amount of P released was 283.16 g/mL [17]. Figure 2 shows the molecular mechanism of PSMs. In the lecithin-containing medium, 47.52 g/mL of P was dissolved over 8 days, although the pH never deviated from the control value of about 7.0. Since the acidity of the culture media does not alter when compared with Ca3 (PO4)2 medium (in which solubilization may have happened via the release of organic acids, the solubilization of phosphorus from lecithin is the result of enzymolysis [53]

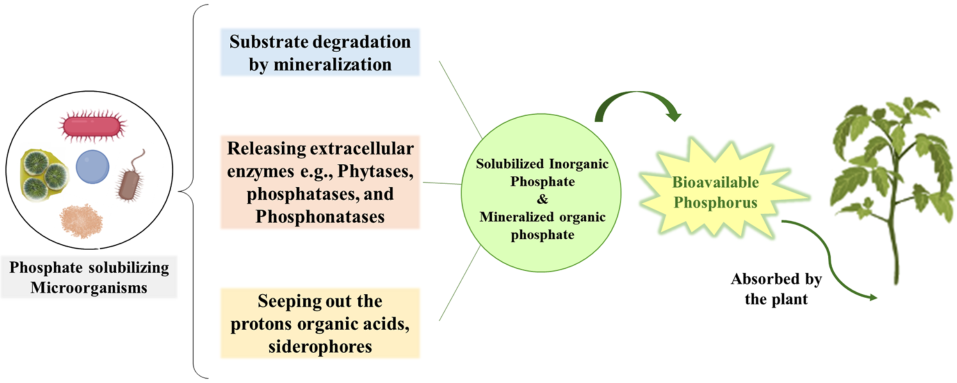


Fig. 2 shows the molecular mechanism of phosphorus-soluble microorganisms, indicating the mineralization process, formation of extracellular enzymes, production of organic acids, and immobilization of organic phosphorus available to plants

4 Soil phosphorous dynamics and rhizosphere interaction

Due to the expulsion of metabolic Carbon from roots, the rhizosphere is defined by a notable increase in the number and activity of soil microorganisms. Besides mycorrhizal fungi, several soil and rhizosphere microorganisms may also improve plant P acquisition by directly enhancing P solubilization or indirectly stimulating plant development via hormones [54] According to various estimates, between 5 and 20% of the carbon produced during photosynthesis is routinely discharged into the rhizosphere, mostly in organic anions, high-simple hexose sugars, and carbon from root renewal and scraped cell [55] Although phosphorus (P) is a crucial ingredient for the growth and development of plants, a significant amount of it still exists in insoluble forms. The emphasis on which Phosphorous Solubilizing Microorganisms solubilize phosphorus and how they interact with plants, as well as the variables that affect PSMSs activity, such as soil pH, temperature, and nutrient availability, is being evaluated currently [56] PSMs can increase phosphorus absorption and plant usage, improving agricultural yield and nutrient use efficiency. The effects of employing PSMSs on the environment include how they may lessen reliance on chemical phosphorus fertilizers, clean up phosphorus-contaminated locations, improve soil health, and increase the sustainability of agricultural systems [57] PSMs adoption in agricultural techniques has the potential to result in a more resilient and sustainable ecosystem overall. In response to phosphorous deprivation, plants may adapt their root architecture, morphology, topology, and distribution patterns [58] Phosphorous-deficient plants often exhibit increased root/shoot ratio, root branching, root elongation, root topsoil foraging, and root hairs. However, only a few species have specialized roots, such as cluster roots [59]. In many plant species, a phosphorous shortage has been shown to increase the length and density of lateral roots and root hairs while suppressing the formation of main roots. Because root systems with bigger surface areas are better equipped to investigate a given volume of soil, root design is crucial for increasing phosphorous acquisition [60] The changed glucose distribution between roots and shoots during phosphorus deprivation is connected to adaptive changes in root development and architecture, and plant hormones, sugar signaling, and nitric oxide may bring on these changes[61]). Root growth is encouraged when plant roots come into contact with nutrient-rich patches, especially when the patches are rich in Phosphorous and/or nitrogen. A reduced root gravitropic response under P restriction is associated with root growth in P-rich topsoil layers, and ethylene may play a role in controlling both responses [62] In a calcareous soil, localized application of phosphates and ammonium greatly increases P absorption and crop development by promoting root proliferation and rhizosphere acidification. By forming mycorrhizal hyphae, mycorrhizal symbioses may expand the nutrient-absorptive surface and improve the geographical availability of P[63]). About 74% of angiosperms' roots have symbiotic relationships with arbuscular mycorrhizal fungus (AMF), which delivers nutrients to plants in exchange for carbon from the plants[64]). The positive impacts of AMF and other microorganisms on plant performance and soil health might be crucial for the sustainable management of agricultural ecosystems. Due to increased direct P absorption by plant roots via the AM route, mycorrhizal plants often grow better than nonmycorrhizal plants in low-P soils. However, the direct root P-uptake route may be downregulated, inhibiting plant development[65]). According to recent gene expression research, plants generate a similar set of mycorrhiza-induced genes, but there is also diversity. The chemical and biological changes caused by roots in the rhizosphere are crucial in increasing the bioavailability of soil P [66] Rhizosphere pH might drop by 2 to 3 units due to root-induced acidification, which significantly dissolves the seldom accessible soil P. The cation/anion uptake ratios and nitrogen assimilation impact the pH shift in the rhizosphere most (Iqbal et al., 2022). Legumes absorb more cations than anions, which causes proton release. Rhizosphere pH fluctuations are also influenced by plant genotypes, microbial activity, and soil buffering capability [67] However, substrate availability, interactions with soil microbes, and soil pH may significantly impact these phosphohydrolases' effectiveness. In the continuity between the soil, rhizosphere, and plant, root-induced bioavailability and acquisition of P concerning root exudation should be thoroughly assessed [68]

5 Microbial biomass for P solubilization

Microbial biomass significantly improves soil fertility through the breakdown of nitrogen fixation, mineralization, denitrification, or immobilization processes. Microbial biomass in the soil helps solve various issues like less phosphorus or nutrient supply to the plant soil[69, 70]. The method of immobilization, in which microorganisms improve P bioavailability by maintaining the P in mineralizable state, prevents fixing in the soils [71] P that has been added or found naturally in the soil is integrated into the bodies of the microorganisms, making it momentarily inaccessible to the plants and stored in organic form [72] P will get immobilized when organic material with a high carbon-to-phosphorus (C/P) ratio (> 300) is added, and P will become mineralized when organic material with a low C/P (C/P) ratio (200) is added[73]). The microbial biomass stores small quantities of phosphorus (1.4–4.7% of the soil's total phosphorus. The carbon and energy supplies provided by P refine manure yields and improve the activity of microorganisms in soil. The physiologically inaccessible and biological presence of phosphorus is connected by soil phosphatases, which catalyze the hydrolysis of organic phosphate esters to orthophosphate [74] Phosphatase enzymes are essential for hydrolyzing P; however, some studies have shown a negative correlation between P concentrations and phosphatase activity. Rhizosphere phosphatase activity increased after compost treatments with added P were applied to mung-bean crops. Dehydrogenase and phosphatase are two additional enzymes that facilitate the mineralization of organic phosphorus or the division of organic matter [75]

6 Factors affecting the process of P-solubilization

PSMSs use severe conditions of surroundings to solubilize the phosphate instead of using a temperate situation like a deficiency of nutrients in the soil, high-temperature climate, or soil of alkaline saline. The conditions in which temperature disturbs the solubilization of phosphate are still contradicting. Still, some researchers state that the ideal temperature in solubilization is 20° or 25 °C, while others prefer 28 °C, or some suggested 30 °C [76] In desert soil, phosphate solubilization was feasible at a low temperature of 10 degrees or a high temperature of 45 degrees. Aerobic bacteria have *bacillus, Pseudomonas, Agrobacterium, or micrococcus genera*, while anaerobic bacteria have *Serratia, Enterobacter, Aeromonas, Paenibacillus*, or *Erwinia genera* [77] To increase the P feeding in plants or mineralization of phytic acid in bacteria, a modest quantity of inorganic phosphate must be added to the rhizosphere [78] Exogenous soluble phosphate also impacted PSMS physiological activity, as the amount of soluble phosphate determines how quickly microorganisms proliferate [79] *Pseudomonas aeruginosa* has phosphate solubilizing strains that grew 25 times faster in excess phosphate than in the absence of phosphate. *B. multivorans* strain WS-FJ9 developed greater soluble phosphate concentration in broth cultures and petri plates, similar to the outcomes of *P. aeruginosa P4* [4] The phosphate solubilizing activity in *B. multivorans WS-FJ9* was greatly immense at absorption of 20 mM or reserved at a 5 mM concentration. It is found that PSB shows sensitivity to soluble phosphate, which was discovered to be severely hampered [80] Similar results were investigated when wheat was inculcated to phosphate solubilizing *Diazotrophic Paenibacillus bejingensis BJ-18 or Paenibacillus*sp. *B1 further enhances* the nitrogen or phosphorus quantity in plants or soil [81] Additionally, when chickpeas inculcated to phosphate-solubilizing fungus like *Penicillium WF6*, the nitrogen-fixing *Mesorhizobium ciceri, and/or PSB Serratia T1* improved nitrogen fixation by increasing the availability and absorption of phosphates [82]

7 Plant growth and propagation, anti-pathogenic activity

Increased plant P absorption and crop yields were based on the quantity of phosphorus bioavailability in the soil [83] With phosphorus fertilization and some rhizobacteria like *Enterobacter sp. RJAL6, Klebsiella*sp. *RC3, Stenotrophomonas sp. RC5, Serratia* sp*RCJ6,* or *Klebsiella*sp. *RCJ4*, the *Lolium perenne* shoot has 29.8% phosphorus content than the uninfected control [84] Under in vitro conditions, when the soil was treated with *Penicillium pinophilum, A. fumigates,*

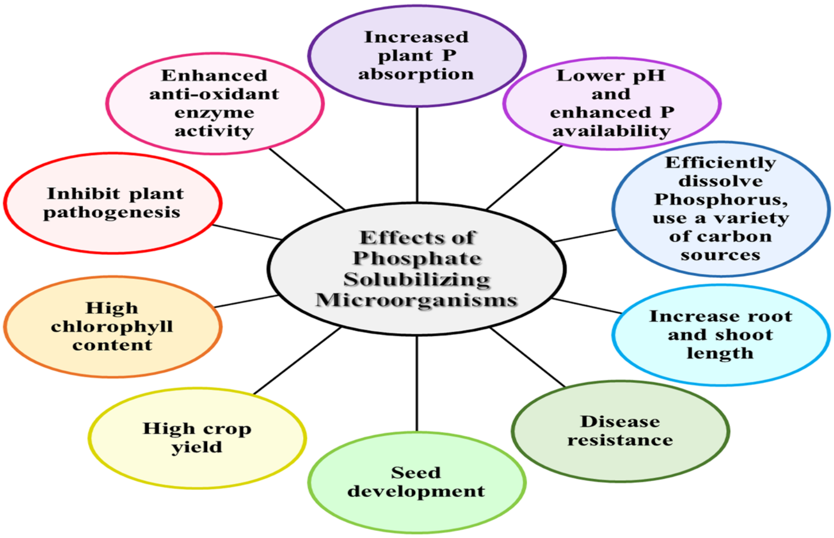


Fig. 3 Role of PSMs in plant growth and propagation, increasing root length, high-yielding crops, seed development, etc.

or *Aspergillus niger,* the super or rock phosphate enhances the phosphorus availability or lowers the Ph value [10]. Using zinc solubilizing bacteria or phosphate isolated rhizosphere as inoculants to boost cotton's growth in semi-arid climates(87)). *Penicillium oxalicum* is a fungus that can efficiently dissolve phosphate and use various nitrogen or carbon sources to improve development or metabolism. *Penicillium pinophilum* or *Aspergillus fumigatus* could increase the wheat and faba bean harvest by inoculating soil or *Aspergillus niger* [86] *Penicillium pinophilum* is considered to be the favorable phosphate solubilizers that fertilized with super phosphate or rock phosphate, increased wheat production by 28 or 32%, and root length grew by 27.7 percent, while shoot length rose by 59.5 percent [87] P plays a crucial role in nutrient absorption, disease resistance, seed development, and crop maturity because of the root system's ability to grow and develop [88] Plant development may be stunted if nutrients are in short supply. Soil-beneficial microorganisms like *Bacillus* sp*Penicillium*sp, *Pseudomonas*sp, or *Aspergillus* spare the most effective or environmentally safe methods for boosting soil phosphorus [89] *Pseudomonas*sp. inoculation causes a rise in accessible P around the rhizosphere and increases the length and volume of wheat roots. *Sorghum bicolor* root-shoot biomass, production, or nutrients were enhanced when Iron-edetic acid was applied *to* phosphate solubilizers *Pseudomonas fluorescence T17-24, Bacillus subtilis P96,* or *Pseudomonas putida P159* in low fertility calcareous soil [90] Plants cultivated in the presence of PSB exhibited considerable enhancements in shoot biomass, nutrient uptake, and chlorophyll content Utilizing processes of growth stimulating adaptability or microorganisms is a significant resource for the manufacture of bioinoculants and, by extension, for agricultural sustainability [91] Pathogenesis in the host plant may be inhibited by the presence of antifungal metabolites produced by phosphate-solubilizing species such as *Bacillus, Pseudomonas, Streptomyces, or Serratia*. Wheat seedlings infected with *Fusarium sp*. were protected by the phosphorus-solubilizing and *Fusarium-inhibiting bacteria, Advenella*sp*, or Enterobacter hormaechei* [92] Solubilizing Phosphates Tomato bacterial wilt is caused by *Ralstonia solanacearum*, although *Pseudomonas fluorescens* may be used as a biocontrol agent. Soybean growth was stimulated by *Trichoderma* spp (2.1–41.1%) and P absorption efficiency was increased (to 141%) [93] Bacteria used as biocontrol agents reduced the wilt prevalence or promoted plant production or growth by producing enzymes like amylase, proteases, or lipases, which target the pathogen's metabolic processes [94] Phosphate-solubilizing *Bacillus subtilis MF497446* reduces cowpea's cadmium absorption by 29.2% and can withstand cadmium concentrations of up to 18 mg L^{-1}. Cadmium stress similarly increased infused seeds' seedling vigor index or germination rate [95] Fig. 3 *shows the role of PSMs in plant growth and Propagation Phaseolus vulgaris* enhanced the production, development, chlorophyll content, or antioxidant activity of enzymes as well as the presence of phosphorus solubilizing strains when combined with nano phosphorus. Development and rhizosphere microbial community regulation in *Ulmus chenmoui* must be advanced after the inculcation of PSB [96] Soil PSMs may use different biogeochemical strategies for using inaccessible kinds of phosphorus, which also helps to improve phosphorus absorption in plants' soil.

8 Impact of phosphorus solubilizing microorganisms on the environment

PSMSs actively participate in the degradation of organic compounds through their involvement in phosphorus mineralization [97] Organic phosphorus compounds, such as those found in plant residues, animal manure, and other organic waste, can be complex and inaccessible to plants. PSMSs produce various enzymes, including phosphatases, which break down these organic phosphorus compounds into simpler, soluble forms of phosphorus [55] This enzymatic activity enhances phosphorus availability for plants and other microorganisms, facilitating the decomposition and recycling of organic matter. PSMSs contribute to ecosystems' overall nutrient cycling [98] By solubilizing phosphorus, they promote its transfer and uptake by plants, ensuring the availability of this essential nutrient. In turn, plants incorporate phosphorus into their tissues, which are later decomposed by microorganisms, including PSMSs, to release phosphorus back into the soil. This cyclic process of organic matter degradation and phosphorus solubilization by PSMSs helps maintain nutrient balance and sustainability in ecosystems [99] Beneficial microorganisms may be employed in reclamation programs, including Rhizobium and Azotobacter, which dissolve phosphate, and blue-green algae[91]). The soil microorganisms are also metabolically adaptable, making them appropriate for nutrient-poor soil growth. When seedlings of planted species are pre-inoculated with microbial inoculants, there is strong evidence that damaged locations prominently revegetate [100]

8.1 Soil Phosphorus to Mediates Environmental P Cycling

Over 80% of phosphors are stationary or difficult to absorb in plants. P is present in the soil in various forms, mostly inorganic (Pi) and organic (Po) P. It indicates the expression of alkaline phosphates or periplasmic acid phosphatase from the PSMs genuine soil; it activates the uncertain ions of biomineralization in polluted soil [101] Extracellular alkaline phosphatase genes are present in the cyanobacterium *Microcystis aeruginosa*, allowing it to use various types of insoluble organic or inorganic P. Total P is often found in greater concentrations in soils than other important nutrients like potassium or nitrogen Another crucial enzyme for Po mineralization is phytase, which is encoded by the appA or phyA genes and releases P from phytate in soil. PSMs have a large microflora that mediates the bioavailability of phosphorus soil and plays an important role in the function of soil [102] It mineralizes minerals of inorganic phosphorus, accumulating significant phosphorus in biomass or organic phosphorus. A macronutrient called phosphorus is crucial for developing plants for plant development or various metabolic processes. One of the principal factors limiting biomass production in terrestrial ecosystems [54] It also contributes to the continual eutrophication of coastal and continental seas. Individual ecosystems include the P cycle, intimately tied to important security concerns of the surrounding environment and human civilization [103] P is immediately stored in aquatic or terrestrial ecosystems, so it is transferred into aerosol-borne phosphorus when fossil fuels and biofuels are burned and released into the atmosphere. In earlier research, climate change, biological activity, and human disturbance have all been believed to impact the worldwide phosphorus cycle significantly [104] Human actions have severely harmed the working of the ecosystem or damaged geochemical stability in phosphorus soil, including creating and using organophosphorus compounds, mining geological phosphorus sources to make phosphorus fertilizers, or releasing animal debris in surroundings [105] The effective use of PSMSs in situ is still in its early stages since its broad application and possible ecotoxicity have not been established. Environmental genomic libraries were created to identify the complete sequencing of unrefined phytase gene [106]

9 Assists biological remediation processes

In reclamation initiatives, soil microorganisms may be employed, including Rhizobium, Azotobacter, bacteria that solubilize phosphate, and blue—green algae[107]). According to research, adding sulfur-oxidizing bacteria to rock phosphate with sulfur, organic matter, PSB, and sulfur has the benefit of increasing the phosphorus attainability of plants [108] The phylogenetic investigation of *Acinetobacter*sp, *Bacillus* sp or *Pseudomonas* spshowed a bioleaching process to eliminate metals from mineral concentrates or low-level ores. It includes *T. thiooxidans, chemolithotrophic bacteria, thiobacillus* or *ferroxidans,* which alters the insoluble sulfides of metals into organic form of metal sulphates [109] Using rock phosphate with *Thiobacillus* as a biofertilizer dramatically boosted the growth and oil production of *Raphanus sativus. The* kind of rock phosphate, the ratio of rock phosphate to elemental sulfur, and the state of the soil and crop are all factors that impact the availability of phosphorus in rock phosphate when combined with elemental sulfur. The maximum percentage of elements' chemical leaching, 0.6%, uses roughly 2-ketogluconic acid (6 g/L), oxalic acid (1 g/L), or citric acid (14 g/L) [110] The formation of the halo zone, which biologically leached PSB's ability, is controlled by the liquid and agar media. *A. aceti* is regarded as one of the top PSB strains for dissolving phosphate [111] Generating various organic acids appears to benefit from using Pseudomonas aeruginosa or Aspergillus ficuum, which is vital in removing environmental pollutants. These elements work with rock phosphate, *Pseudomonas* spp*Burkholderia* spp*and Enterobacter* spp*Leclercia adecarboxylata* was introduced and eventually became the dominant micro flora in the soil's microbial community, increasing lead passivation efficiency and phosphate usage rates [112]

10 Successful biological fertilization using PSMs

Biological fertilizers do not harm ecosystems and may be used without worry as various compounds, sugars, lipids, or nucleic acids are present in it. *Bacillus, Rhizobium, Pseudomonas, Candida*, and *Aspergillus* can promote soil health and fertility [113] About 40% of the existing Phosphate Solubilizing Bacteria showed nitrogen-fixing activity, while 27% showed exceptional phosphate-solubilizing capacity. Soil inoculation with *Pseudomonas* and *Bacillus species* improved wheat output [114]). The inoculation of the Penicillium, Fusarium, or Aspergillus species significantly improved rhizosphere soil of faba or haricot beans, sugarcane, cabbage, or tomatoes. Based on the solubility index, 167 (46.52%) out of 359 fungi could solubilize the inorganic phosphate within the range of 1.10–3.05. *Penicillium soli, Talaromyces yunnanensis* or *Gongronella hydei* showed the highest phosphate solubilizing activity [115] In addition to thriving in acidic conditions, these organisms also have a remarkable capacity for releasing soluble phosphorus with the help of phosphorus-bearing difficult molecules [121)] Phosphate mine *Galactomyces geotrichum* can convert insoluble phosphate into a usable plant form. Different molecule components or energy converter methods like GTP, ATP, or photosynthesis are involved. The phosphorus deficiency activates physiological or cellular changes, which is considered a limiting factor in the growth of plants [117] Out of the total quantity of phosphorus applied to fertilizers, the average productivity is between 20 and 25%, changing its physical, chemical or biological properties. It also negatively affects soil quality or agriculture production [118] The physical or biological characteristics of soil are also affected by excessive fertilization at high doses. Agricultural soils often have an abundance of P due to P fertilizers. Adsorption and fixation processes cause greater than 80% of applied phosphorus fertilizers to be lost in the soil [119].). Table 1 shows the Capabilities of phosphorus solubilization as biofertilizers. PSMs offer a practical and cheap solution to the P shortage and plants' subsequent absorption [120–123]

11 Conclusion and future perspectives

Using phosphate-solubilizing microorganisms (PSMs) in sustainable agriculture environments holds great promise for addressing the global challenge of phosphate deficiency in soils. PSMs offer an eco-friendly and cost-effective solution to enhance phosphate availability to plants, improving crop productivity and reducing reliance on chemical fertilizers. The application of PSMs in sustainable agriculture offers several key benefits. Firstly, PSMs can solubilize inorganic phosphates, making them more accessible to plants. This can significantly improve nutrient uptake and utilization, particularly in phosphorus-deficient soils. By enhancing phosphate availability, PSMs contribute to increased crop yields and improved agricultural sustainability. Moreover, PSMs can potentially reduce the environmental impact of phosphate fertilizer use. Chemical fertilizers often result in nutrient runoff and water pollution, leading to eutrophication and damage to aquatic ecosystems. By promoting the natural mobilization of phosphates, PSMs can help minimize the need for excessive fertilizer application, thus reducing environmental pollution and preserving water quality. In addition to their direct impact on plant nutrition, PSMs exhibit other beneficial traits. They can promote plant growth by producing growth-promoting substances, enhancing root development, and suppressing pathogenic organisms through competition and antibiosis. These characteristics further contribute to sustainable agriculture practices by reducing the need for synthetic chemicals and fostering a balanced and resilient agroecosystem. To increase crop output in environmentally responsible agriculture, PSMSs might replace inorganic phosphate fertilizers to meet plants' phosphorus needs. However, successfully utilizing PSMs in sustainable agriculture requires further research and development. Efforts should optimize PSM formulations, improve their efficacy under diverse soil and climatic conditions, and understand the mechanisms underlying their phosphate-solubilizing abilities. Additionally, exploring the synergistic effects of combining PSMs with other sustainable agricultural practices, such as organic farming or precision nutrient management, can enhance their effectiveness.

Table 1 Shows utilization of phosphorus solubilizing microorganisms as an effective biological fertilizer

Phosphorus Solubilizing Microorganisms	Plant/crop	Effective Output of PSMs as a Biological Fertilizers
Pseudomonas aeruginosa, *Bacillus subtilis*	Rice	Increased shoot length, root length, and dry weight of plant by 154.7%, 237.6%, and 210.3%
Pantoea agglomerans	Maize	Improved shoot length, number of cobs/plants, number of seeds/cobs by 11.2%, 13.9%, 11.8%
Bacillus polymyxa	Wheat	Improved plant height, spikelet/spike, Grains/spike by 16.6, 16.2%, 45.6%
Pseudomonas sp.	Chilli, Maize	Increased shoot and root fresh weight/plant by 11.2% and 7.5%
Enterobacter sp., *Serratia* sp.	Soybean	Enhanced shoot and seed weight up to 13.8% and 16.1%
Burkholderia cepacia	Peanut	Increased average yield rate of 11.1%
Aspergillus awamori	Mungbean	Increase shoot and root length by 50.9% and 27.6%
Bacillus pumilus	Potato	Increased stem length by 79.3%
Bacillus M-13	Sunflower	Increased seed and oil yield by 15% and 24.7%
Bacillus aryabhattai, *Pseudomonas auricularis*	*Camellia oleifera*	Improved plant height and biomass by mixed inoculation (1:1) by 47.2% and 103.8% under no phosphate fertilizer
Penicillium guanacastense	*Pinus massoniana*	Fungal suspension and extracellular metabolites in the strain promoted the seedling shoot length by 97.7% and 59.5%
Pseudomonas, *Burkholderia*, *Paraburkholderia*, *Novosphingobium*, *Ochrobactrum*	Chinese fir	Increased plant height (up to 1.26 times), stem diameter (up to 40.7%), and the biomass of roots stems, and leaves (up to 21.3%, 29.1%, and 20.8%)

More research is required for their metabolism investigation or segregation from variant ecological niches to improve PSMs' capabilities. PSMs aren't the only microorganisms that might benefit from a metagenomics strategy to increase and introduce phosphate solubilizing efficiency.

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