Beneficial Role of Phosphate Solubilizing Bacteria (PSB) In Enhancing Soil Fertility Through A Variety Of Actions On Plants Growth And Ecological Perspective: An Updated Review

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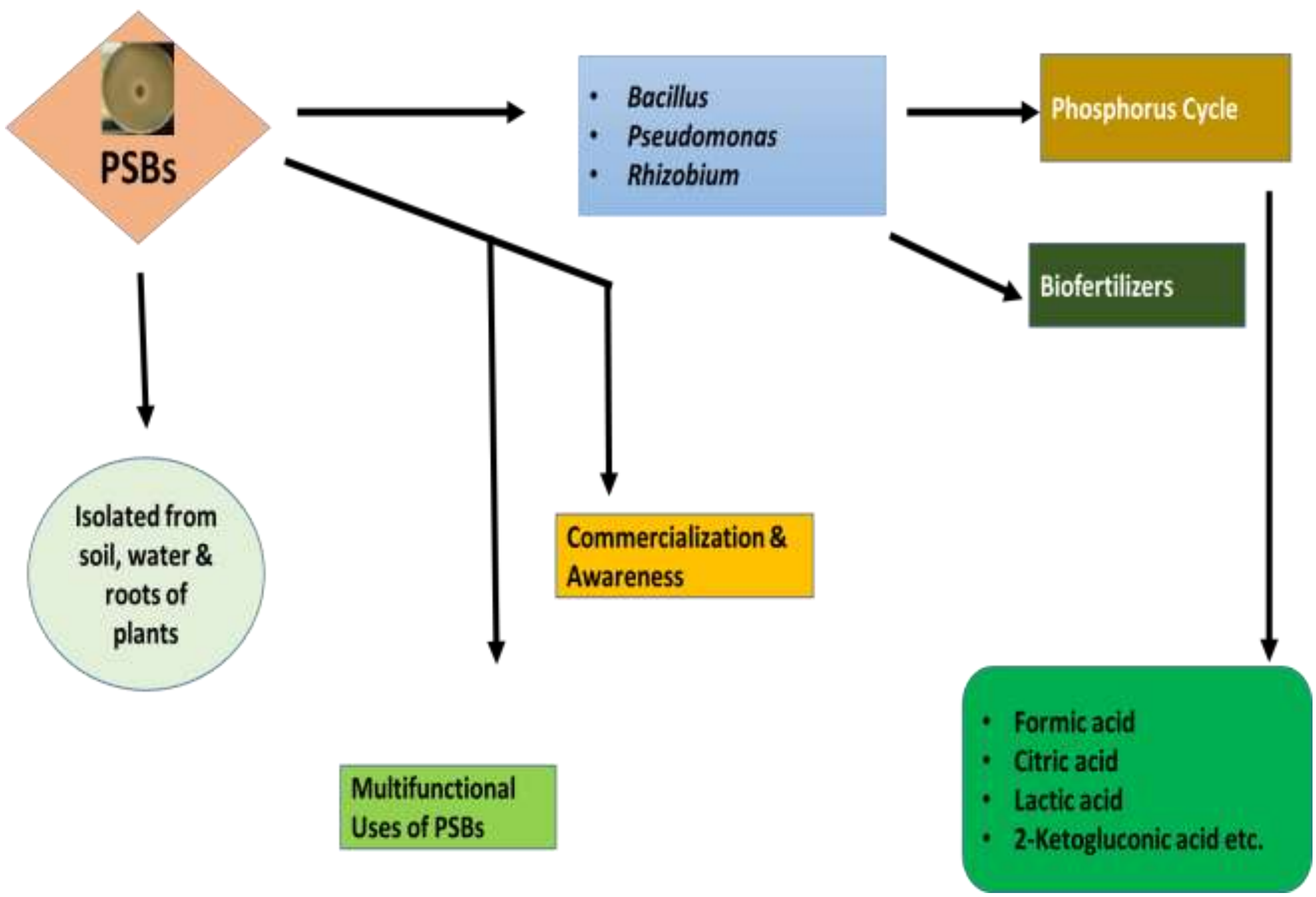
Abstract- It has been established that Phosphorus, a macronutrient necessary for all life on Earth, is a critical nutrient element that limits plant development and productivity. Chemical phosphate fertilizer has historically been used to address the P deficiency issue in agricultural productivity. Still, its use has been constrained by the non-renewability of raw materials and the unfavorable impact on the ecological health of the environment. Phosphate-solubilizing bacteria (PSB) belong to a group of microorganisms that have the capabilities to transform insoluble Phosphate into soluble Phosphate, making it readily accessible to plants are considered to be an important key figure in mineralization, making its favorable use as biofertilizers in soil sustainability. PSB can solubilize Phosphorus by secreting low-molecular-weight acids like lactic, formic, malonic, gluconic, and citric, which can dissolve the mineral form of Phosphorus. PSB has been shown to increase crop yields and improve soil structure. Their effectiveness has multiple roles in increasing soil sustainability, the biological leaching of heavy metals, and enhancing Phosphorus. The PSB can be removed from various settings, including soil, water, and plant roots. *Pseudomonas*, *Rhizobium*, and *Bacillus* are a few typical PSB examples. Furthermore, the incidence of heavy metals in agricultural soils performs functional importance in the phosphorus-solubilizing bacteria biological remediation process. PSB are crucial bacteria that may solubilize Phosphorus and increase soil fertility. One milligram/kilogram of phosphorus solubilization is often found in soil. Their usage as biofertilizers has the potential to increase crop yields while lowering agriculture's negative environmental effects. This review goes into great detail about the numerous roles that PSB has played.

Key words- Biofertilizers; Soil Fertility; Soil microbes; Organic Acids, P solubilization, P Immobilization, Plant-Growth Promoters, Phosphate Solubilizing Bacteria

Graphical Abstract



INTRODUCTION

P is an indispensable nutrient for plant development, playing a crucial role in metabolic processes and serving structural, energetic, and regulatory functions for plant development and growth (Silva *et al.*, 2023). The phosphorus nutrient is present in such a modest amount compared to many other essential components that the soil must endure. As the nitrogen-to-phosphorus ratio in most agricultural soils is typically between 3:1 and 5:1(Qaswar *et al.*, 2019), the ratio of potassium to Phosphorus varies by soil type. The ratio can vary from close to 1:1 in some circumstances to 2:1 to 5:1 in others (Naciri *et al.*, 2022). Even though these are needed in lower amounts, micronutrients including boron (B), molybdenum (Mo), manganese (Mn), copper (Cu), and iron (Fe) are crucial for plant growth. (Desta *et al.* 2023). The shortage of Phosphorus is characteristic in various soils since levels rarely rise above 10 µM. Phosphorus levels in soils range from 200 to 2000 kg per hectare of the top 15 cm of soil, with the typical value being close to 1000 kg (Babalola *et al.*, 2010). The amount readily accessible to plants is often a small portion of this total Phosphorus. Fixation is the process through which Phosphorus binds to soil particles or transforms into insoluble compounds. Particularly in alkaline soils or soils heavy in iron (Fe), aluminum (Al), or calcium (Ca), this fixation takes place. In comparison with additional nutrients like nitrogen (N) or potassium (K), Phosphorus is less mobile in soil (Safdar *et al*., 2023). Because it tends to bind to soil components like clay and organic matter, Phosphorus has the capacity for adsorption, making it less easily available for plant uptake. (Dhaliwal et al 2019). The dissolution of Phosphorus from decaying matter through decomposition is a lengthy process that calls for microbial activity and breakdown. Organic matter in the soil includes Phosphorus in organic forms (Diarra *et al.,* 2023). According to recent studies, plants can use only 0.1 percent of phosphorous in the soil, even though soils contain between 95 and 99 percent of their total phosphoric content in insoluble phosphates. This type of dichotomy pattern is formed only because of its insoluble forms that plants do not consume. Since Phosphorus generally causes metals like aluminum and iron to react when low pH conditions are present (Bilal *et al.,*2021), it is the main reason for the formation of insoluble substances when low sedimentary and acidic soil is present. This feature of alkaline soil may also exist as calcium phosphates. Yet, the phosphorus nutrients become immediately available with a pH range between 6 and 7. Recent research has shown that PSBs (*Pseudomonas*, *Burkholderia*, *Bacillus*, *Rhizobia*, *Mycobacterium*, and *Pantoea*) interact with phosphate fertilizers to boost phosphorus uptake (26 %) and wheat grain output (22%) while reducing fertilizer input (30%) (Ahmad *et al.,* 2021). Using microorganisms as bioinoculants is risk-free and is an effective approach to enhance phosphorus solubility. Phosphate ions in the soil solution that plants easily assimilate are soluble inorganic Phosphorus. Inorganic Phosphorus that is insoluble in water is typically attached to soil particles or minerals like apatite and metal phosphates. Although organic Phosphorus is found in complex organic compounds made from living or decomposing organic materials, plants cannot quickly absorb it. (Tian *et al.,* 2021) Microorganisms that solubilize Phosphorus also produce phytases and phosphatases enzymes that make it simple for plants to acquire Phosphorus, as well as organic acids like citric acid, malonic acid, and lactic acid siderophores, which function as an ion chelator (Grzyb *et al.,* 2020). Another characteristic of PSBs is the encouragement of plant growth. These improve plants' general growth or development in both stressful and non-stressed conditions. PSBs are excellent growth promoters because they release plant growth hormones like cytokinins, auxin, and gibberellins, upregulating nitrogen fixation and solubilizing the potassium (Tiziani *et al.,*2020). They remove antibiotic or antifungal substances that protect plants from various diseases (Abbas *et al.,* 2019). Moreover, it can help with the bioremediation of soil that heavy metals have damaged. Many PSBs release enzymes 1-Aminocylopropane-1-carboxylic acid (ACC) deamination and reduction of ethylene during plants facing stress conditions (Nadeem *et al.,* 2016). So, Microorganisms are vectors of sustainable agriculture, as they can make nutrients available to previously inaccessible plants, minimizing the need to apply chemical fertilizers, meet the requirements of sustainable agricultural plans, and maintain ecological balance (Doilom *et al.,*2020). PSBs are useful because living plants are soluble in Phosphorus and are the most prevalent and significant source of Phosphorus in plant nutrition. Phosphorus can only be absorbed as soluble ionic Phosphate (Pi), such as HPO_4 or H_2PO_4, and it is necessary for the development and growth of various plants (Abbasi *et al.,* 2015). Thus, these compounds are used on soils as phosphate fertilizers. In ancient times, animal excrement was frequently used to fulfill the Phosphorus requirement in plants to enhance its growth and development. (Ibrahim et al 2022). Phosphorus, which is organically bound, enters the soil through various processes, such as the decay of deceased animals, animal excrement, and plant decomposition (Smith *et al.,*2022). Yet, in those times, there was little knowledge of how microbial populations affected soil fertility. These fertilizers' production depends only on the choice of favorable soil bacteria that supply nutrients in soluble and usable forms. It can also improve plant development patterns (Rawat *et al.,*2021). According to a survey, using these inoculants to give frequently available nutrients in root activity zones becomes the production source of a wide range of other microbial flora. Bacterial communities associated with the plants are present with the special property of increasing the consumption and availability of nutrients (Silva *et al.*, 2021). For example, *Pseudomonas*, *Rhizobium*, and *Bacillus* are thought to be the most effective organic and inorganic Phosphate solubilizers because they may enhance the absorption and availability of important macronutrients such as Phosphorus. Microorganisms can release a wide range of metabolites, such as synthetic acids. (Nunes *et al.*,2020). Evaluation of phosphorus-solubilizing activity can be done by producing a variety of organic acids. The cations attached to Phosphate are chelated by these synthetic acids with the help of carboxyl or hydroxyl groups, which eventually causes them to change into soluble forms (Alabama *et al.*,2022). Several microbiological activities or mechanisms, including the extrusion of protons and generation of organic acids, are intricate in phosphate solubilization. PSBs produce small-molecule synthetic acids, primarily keto gluconic or gluconic acids, which remove Phosphorus from the soil (Oteino *et al.*, 2015). They also lower the pH in the rhizosphere (Alewell *et al.*, 2020). As a result, they reduce agricultural output and harm food quality and quantity. As a result, several compounds have been developed to protect plants from diseases, though they have various disadvantages (Yu *et al.*, 2021). Again, bio-control has emerged as a practical method to counteract the unfavorable impact of these infections on plant development. In addition to phosphorus solubilization, these bacteria may create compounds that help plants develop, for example, indole acetic acid (IAA). It boosted the growth of plants and showed stress resistance. (Chen *et al.*, 2022). The use of PSB as biofertilizers in nutrient-deficient soil can decrease the number of synthetic fertilizers and boost crop output. As a result, PSBs can be used as biofertilizers to enhance crop production or soil fertility (Abdelgalil *et al.*,2022).

Phosphate-Related Soil Issues

Phosphorus is a very crucial macro-element for the growth or development of various plants. Many essential plant processes, such as root growth, stem or stalk strength, flower or seed development, crop development and product quality, and plant defense against diseases, are all influenced by phosphorus nutrition (Azam *et al.*, 2023). Many kinds of Phosphorus can naturally exist in the soil solution. It consists of two main categories: insoluble organic Phosphate and insoluble inorganic Phosphate. However, only a small portion of the Phosphorus exists in many soil solutions (0.1% or 1 ppm), easily accessible in plants since it is poorly soluble and fixable in soils (Wijaya *et al.*,2022). The roots absorb Phosphorus as HPO_4- and H_2PO_4- which depends upon soil pH. A large amount of inorganic soluble Phosphate is used as chemical fertilizers, which become immobilized and inaccessible to plants. Many reactions start when manure phosphate and fertilizers come in contact with the soil, making the Phosphate less available and soluble. However, Phosphorus in soil and degree of fixation are mainly linked to different soil parameters like Fluctuation in temperature, change in pH, contents present in moisture, and microelements existing in soil (Ibáñez *et al.*,2021). Iron oxides, free aluminum, and hydroxides in soil with great acidity largely fix Phosphorus. Soil has low Phosphorus levels, often less than potassium and nitrogen. The amount of Phosphorus in soil varies from 200 to 2000 kg phosphorus/ha of the top 15cm of soil, with an average of around 1000 kg. (Olagunju *et al.*, 2021) Throughout the world, very little accessible Phosphorus is present on 5.7 billion hectares of land to support optimal production of crops. Unlike nitrogen, no significant atmospheric phosphorus supply can be converted into physiologically accessible Phosphorus. Hence, a shortage of Phosphorus significantly limits crop development and output (Djuuna *et al.*, 2022). When roots absorb the phosphorous, a small portion is transformed to form complexes with calcium-rich soil and aluminum or iron in acidic soil; hence, phosphorus deficiency issues must be ameliorated, for instance, using phosphorus fertilizers to maintain production (Shen *et al.*, 2011). However, indiscriminately using these phosphorus-containing fertilizers for an extended period causes (a) disruption of microbial diversity and its related metabolic processes, (b) reduced soil fertility, and (c) lower the yield of agronomic crops (Tian *et al.*, 2021). In actuality, it is clear that agricultural soils have many phosphorus reserves.

Approximately 95-99% of these reserves are available in insoluble phosphates that plants can hardly use (Wilson *et al.*, 2019). It has been hypothesized that phosphates accumulated in agricultural soils will be enough to provide the highest crop yields worldwide for around 100 years (Liang *et al.*, 2020). Chemical fertilizers are frequently utilized to satisfy the phosphorus needs of crops, as opposed to making an effort to exploit these reserves. However, as fertilizer production depends on substances like nitrogen, Phosphate, and potassium, prolonged usage of chemical fertilizers has raised significant environmental problems and concerns about the scarcity of pricey inputs. This background makes mineral phosphate solubilization a hot topic (Sadaf *et al.*, 2022). Population pressure and technological advancements in agricultural operations have substantially impacted the dynamics of Phosphorus in soil. Around 67% of agricultural land worldwide lacks sufficient Phosphorus. Agrochemical applications in soil are dangerous, whereas Phosphorus recovers only 10-20% of the efficiency of crops (Ven *et al.*, 2016). Due to fertilizer input, the maximum phosphorus content of 0.1-5mg is typically close to the soil surface. On the other hand, subsoils have low levels of dissolved Phosphorus 0.1mg. Inoperative Phosphorus in soil and high soil fixation capability are just because of precipitation, immobilization, and complexation, which results in a shortage of Phosphorus available to plants (Rao *et al.*, 2010). The phosphorus immobilization in the soil is largely determined by the soil's pH (Chávez *et al.*, 2022). The carbon, an energy source for microbes, rapidly mineralizes P in soil. It is just because of microbial iron III reduction. An optimal concentration of Phosphorus in soil is maintained for healthy crop growth and yield (Stosiek, *et al.*,2020). According to a recent study of phosphorus soil, a different approach to the availability of Phosphorus is required rather than using pesticides (Lang *et al.*, 2020). In this article, we will discuss the beneficial role of Phosphate solubilizing bacteria, its molecular mechanism, and how PSB is vital in enhancing soil fertility through different actions.

Different Phosphate Solubilizing Bacteria

Soil is considered to be the most diverse microbiome hotspot. Organisms known as PSBs can transform insoluble Phosphorus into a form that is accessible to plants. They are numerous in soil, and to check the strength of phosphate soil, methods like qualitatively and quantitatively may be applied (Table 1) (Johan *et al.*,2021)

Table 1: Different phosphate-solubilizing bacteria occurrence.

Different Phosphate Solubilizing Bacteria Occurrence	Citations
Agrobacterium, Arthobacter, Bacillus, Klebsiella, Burkholderia, Rhodococcus, Enterobacter, Pseudomonas, Rhizobium, Kushneria, Alcaligenes, Erwinia, Bradyrhizobium, Flavobacterium, Serratia, Paenibacillus, sinomonas, Thiobacillus, Acinetobacter, Salmonella, Azotobacter, Ralstonia	(Iyer 2019; Divjot *et al.*,2021)

Numerous bacterial taxa, including *Pseudomonas*, *Bacillus*, *Enterobacter*, *Pantoea or Serratia*, *Arthobacter*, *Burkholderia*, *Rhizobium*, *Rahnella aquatilis HX2*, and *Leclercia adecarboxylata*, are among the most potent PSBs (Caulier *et al.*, 2018). Due to their metabolic activity and a noteworthy contributor to integrated nutrient management in the soil, this soil microbiome is crucial in soil health. Also, it enhances the plant uptake of soil-based nutrients (Mendes *et al.*,2020). The type of bacteria considered to increase agricultural production as the effectiveness of the bioinoculant depends on the inoculum and the environment. The PSBs also perform various tasks by synthesizing growth-promoting chemicals; PSBs are renowned for promoting the growth and development of plants (Cantin *et al.*, 1999). Numerous studies have been carried out to examine how Phosphate solubilizing microorganisms impact plant growth promotion in both stress and unstressed settings.

Auxin, gibberellins, or cytokinins, among other hormones that promote growth produced by Phosphate solubilizing microorganisms, encourage division of cell, root and shoot growth, germination, flowering, and xylem distinction (Cui *et al.*, 2022). The inoculation of soybeans with *Bacillus tequilensis*, a unique strain, is demonstrated to enhance under heat stress plants' shoot length leaves ultrastructure and pigment required during photosynthesis. (Kailasam *et al.,* 2022). Chen et al. identified the new strains in the field of biofertilizers, like *Pseudomonas plecoglossicida,* which is extracted from the soybean rhizosphere and solubilized the 75.39 mg L-1 amount of Phosphorus as well as producing plant growth regulators such as indole acetic acid almost 38.89 ppm (Chen *et al.,* 2021). Phosphorus is solubilized by *Trichoderma harzianum* up to 288.18 ug /ml. The strain comprises 21.14 ug/ml of indole acetic acid. In contrast to uninoculated plants, fungi-treated *Solanum Lycopersicum L*. plants showed upregulate root and shoot biomass, leaf number, and area (Mahmood *et al.,* 2022). Various popular bacteria that dissolve Phosphorus in various concentrations and release phytohormones have recently been described. When the host defense mechanism shows binding, the hormones of bacteria stop preventing certain fungi infections. These findings suggest these microbes can be used for phosphorus balancing and general plant development (Singh *et al.*,2020). The ability of PSBs to produce the deaminase enzymes, which lowers the level of ethylene in stressed plants, is one of its remarkable characteristics. Stress causes plants to produce more ethylene, slowing down plant development. Since deaminase enzyme 1-aminocyclopropane-1-carboxylic acid (ACC) converts ethylene precursor to ammonia or –ketobutyrate, it lowers ethylene excessively in plants and aids in their development and survival under stressful environments (Mei *et al.*,2021). Those Plants that release ethylene precursor enzymes engulfed through bacteria found in plant tissues and cleaved through ACC deaminase enzyme are intertwined to ACC deaminase-producing PSBs. Bacteria utilized the final result of the following reaction of ammonia as a supply of N_2 for growth, lowering the level of stress ethylene in plants (Iyer *et al.*,2019). PSBs release auxin in response to interactions between plants and ethylene precursor, producing solubilizing microorganism that causes biological changes in plants like increased biomass growth and root length. Stress increases the function of the enzyme ACC synthase and ACC oxidase, which first produces a tiny peak of ethylene (less than 10 g/L), which prompts the transcription factor of defense genes in various plants, and then larger, detrimental peak of ethylene (more than 25 g/L). As ACC synthase produces a lot of ACCS, the bacterial ACC deaminase is simultaneously active. This is how ACC deaminase enhances plant growth under environmental stress by reducing the greater peak of ethylene by 50-90% (Anand *et al.*, 2021). ACC deaminase- and Phosphorus- solubilizing new strain *Bacillus subtilisRhizo SF48* promoted tomato plant development (Ahmed *et al.*,2022). The level of solubilized Phosphorus (10g/ml) in microorganisms that dissolve Phosphate also specifies plant growth enhancers. *Nll-0907, Nll-0929, and Nll-0934* are two different species of *Enterobacter aerogenes.* The *Unguiculated vine* species of *Enterobacter asburiae*, which increases seedling biomass and root, shoot length, siderophores, HCN production, and leaf diameter, all increased in the infused plant (Mohammed *et al.,* 2018). *Zea mays* (L.750.00) as an *Acinetobacter rhizophaerae BlHB 723* treated plants, root shoot phosphorus content increases, and plant height and length increases (Liang *et al.*,2020). Under the inoculated treatment, the given phosphorus and calcium substance of the soil is greater as *Pseudomonas putida, Bacillus subtilis, PSRB7 Azotobacter species, PSRB19 Enterobacter, Lycopersicum esculentum PSRB6, and PSRB32143.00 141.00 100.00 126.00* when compared to control, treated seedlings have a low incidence of *Fusarium* wilt and higher root shoot biomass ACC ethylene precursor enzyme, IAA, and hydrogen cyanide in plant by raising the amount of catalase and superoxide dismutase in plants processed with microorganisms (Adélaïde *et al.*,2022). The level of inoculated plant seed development rate is increased. Munir et al. qRT-PCR research showed that treated plants had a low ethylene-responsive factor (SlERF84). The researchers suggested that this unique strain enhances plant growth or protects the tomato plant from further drought stress damage. According to this research, the ACC deaminase enzyme in microorganisms' benefits agriculture by boosting agriculture yield and increasing plant tolerance to extreme stress conditions (Munir *et al.*,2019). Several mechanisms like lytic enzyme formation, induction of resistant factor, competitive root colonization and allelochemicals, growth of plant help PSBs regulate a plant disease due to pathogens. Many phosphate-solubilizing species, including *Serratia, Streptomyces, Pseudomonas,* and *Bacillus,* release antifungal compounds that inhibit disease in the host plant, including peptaibols, terpenoids, pyrrolnitrin, daucans, phenazines, and polyketides. According to different investigations, *Enterobacter PSDM10, Advenella sp. PSDM17* and *hormaechei PSDM10* isolated from treated water were found to solubilize Phosphorus and prevent *Fusarium sp.* infection in wheat seedlings. (Murgese *et al.*,2020). It has been determined that *Pseudomonas fluorescence* acts as a biocontrol pesticide for the bacterium *Ralstonia solanacearum* that causes infection wilt in tomatoes. These types of biocontrol agents create proteases, amylases, and lipase enzymes that interfere with the metabolic processes of pathogens. As a result, plants that bind with these microorganisms show high growth and development and less wilting. Due to their ability to lower agricultural output and harm food quality, pathogens seriously threaten plant health. The PSBs with biocontrol activity can reduce pathogen infestation in crops in an environmentally friendly manner and are a potent substitute for synthetic pesticides used to control phytopathogens. Many microbial strains can remove dangerous substances in surroundings, like herbicides, pesticides, organic solvents, and xenobiotics that harm plants, soils, people, and animals (Teng *et al.*,2013). Cadmium levels up to 18 milligrams can be tolerated by the phosphorus-solubilizing *Bacillus subtilis* MF497446, which can also decrease the cowpea cadmium uptake by approximately 29.2 percent. Moreover, under cadmium stress, the strain enhanced the seed germination in infused seeds (up to 9mg/kg).

Bioremediation activity of PSB

The PSBs are a practical and simple way of cleaning up heavy metal-contaminated soil. Such PSBs tolerate heavy metals and improve phytoremediation efficacy in contaminated soil. Promoting the optimum PSB and plant interactions is crucial for extensively cleaning hazardous soil. According to several research, PSBs improve the efficiency with which crops use Phosphorus and their ability to absorb Phosphorus while encouraging crop development and yield (silicon, iron, and phosphorus sources) (Myo *et al.*,2019). When combined with nano phosphors (0.1g/L), for example, the phosphorus-solubilizing bacteria *Pseudomonas cepaceae* and Pseudomonas mallei improved the growth, yield, chlorophyll content, photosynthetic efficiency, and antioxidant enzyme activity in calcareous soil. These enzymes included superoxide dismutase, proline dehydrogenase, catalase, and ascorbate peroxidase. According to reports, increasing the amount of soil nitrogen and Phosphorus boosted land plant vegetative development. Fe EDTA was applied with phosphate solubilizers like *Pseudomonas putida P159, Bacillus subtilis, and Pseudomonas fluorescens T17-24* to improve the yield of sorghum bicolor. The plants with the newly discovered strain *Serratia polymathic BMA1* increased dry weight by 76 % and solubilized 450 mg/L phosphorus (Nacoon *et al.*,2020). Compared to control plants, the treated plants root and shoots have three times greater phosphorus contents. In phosphorus-deficient soil, the group of phosphate bacteria (*Klebsiella, Klebsilla. RCJ4, Stenotrophomonas, Enterobacter sp. RJAL6,* and *Serratia sp. RCJ6)* with fertilization of Phosphorus increase the content of Phosphorus in *Lolium perenne* shoot (29.8 %) when relating to vaccine free control. The PSBs that were injected with seeds such as *Pseudomonas linii BFS 112, Pseudomonas koreensis TFD26, and Enterobacter asburiae TFD26* were demonstrated by a researcher. These results suggest that PSBs boost plant phosphorus content or overall development and health in normal and stressful situations (Nacoon *et al.*,2020).

2-Mechanisms Of Phosphate Solubilization By Bacteria

Many Phosphate solubilizing bacteria are generally approved to be entangled in bacteria. Various other organisms, such as fungi, archaea, and actinobacteria, are involved in phosphate solubilization. Figure 1 demonstrates the phosphate solubilizing process in which the insoluble form of Phosphate is transformed into the soluble form of HPO_4^{-2} OR $H_2PO_4^{-1}$ (Nadal *et al.*,2022).

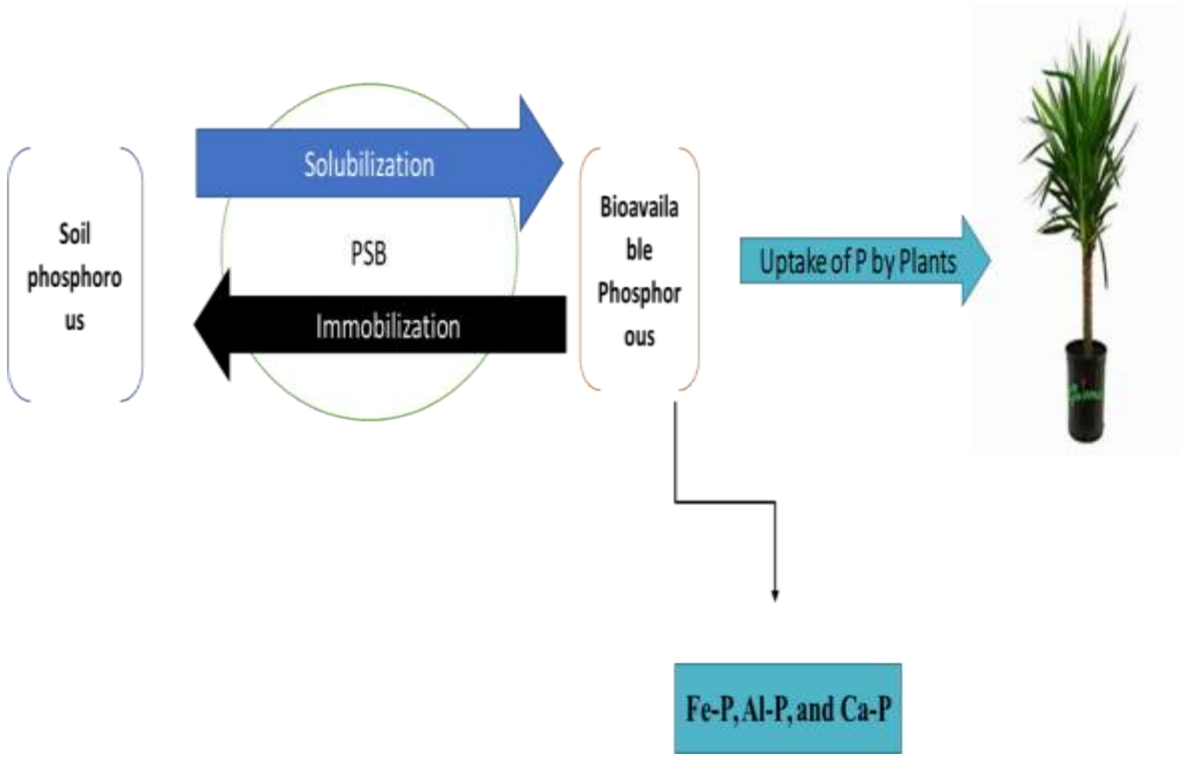


Figure 1. Phosphate Solubilizing Mechanism done by PSB by converting insoluble P to soluble phosphorous, readily uptake by plants from soil

The key components of this mechanism are chelation, acidification, and the production of a wide range of organic acids. Along with the acidification process, the formation of organic acid results in the immobilization of insoluble phosphate molecules. Triphosphate can be converted into diphosphates using a low molecular weight acid. These triphosphates make soluble Phosphate available to plants (Wendimu *et al.*, 2023). Each species of PSB produces different kinds of low molecular weight acids in varying amounts. Among them are citric, oxalic, fumaric, acetic, and tartaric acids. The synthesis of various low molecular weight organic acids by various phosphate-solubilizing bacteria is depicted in Figure 2.

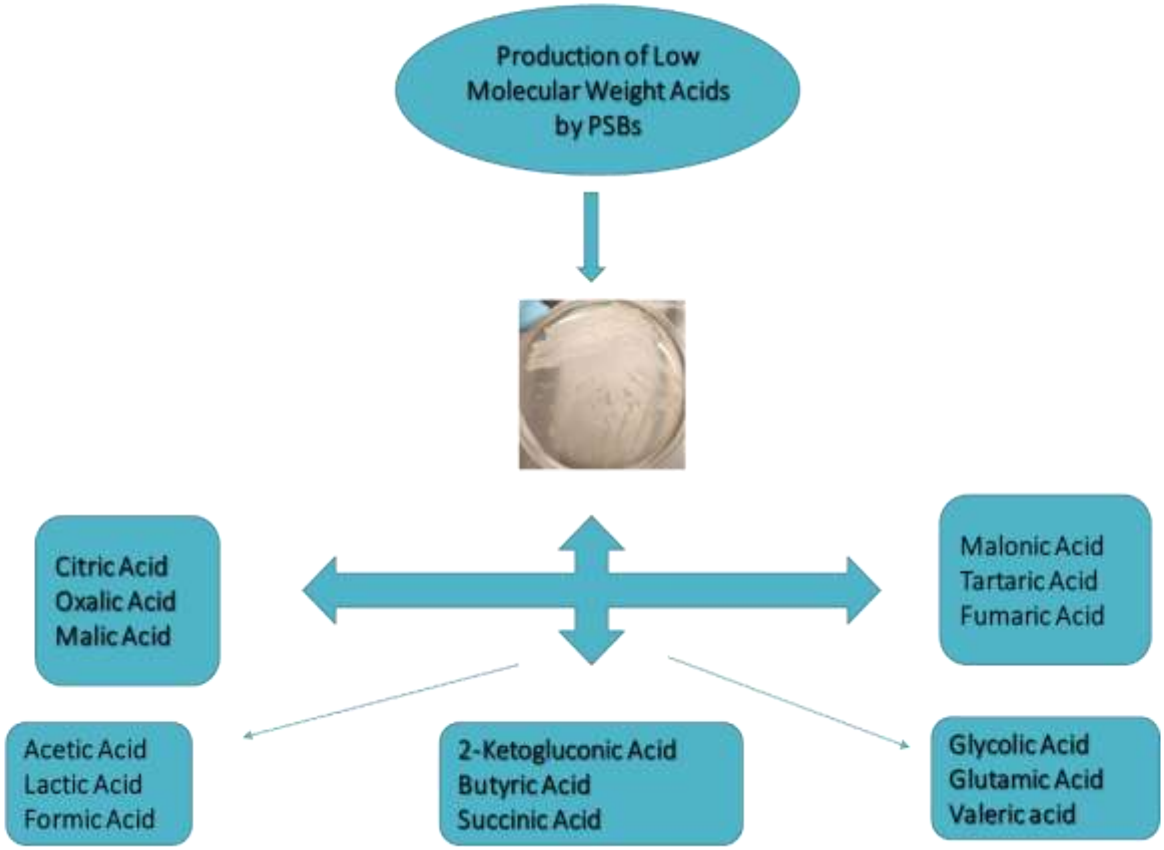


Figure 2. Production of different low molecular weight organic acids by different Phosphate-solubilizing bacteria

Numerous organic acids produced by PSBs can be identified using enzymatic processes like high-performance liquid chromatography (HPLC) and liquid chromatography-mass spectrometry (LCMS). Through the solubilizing activity, *Trichoderma* strains produced low molecular weight acids including phytic, citric, and ascorbic in soybeans (Buddhi *et al.*,2012). The insoluble processes mix with these acids, causing a pH drop and forming anions and cations. The composition and potency of low molecular acids produced by Phosphate solubilizing bacteria directly affect the solubilization index's effectiveness. Compared to aromatic acids, aliphatic acids are more frequently successful at phosphate solubilization. The oxidation of nitrogenous and sulfur compounds by *thiobacillus* and nitrifying bacteria results in the generation of acids like HNO_3 and H_2SO_4, which also contribute to acidification through CO_2 evolution and the production of carbonic acid. Numerous PSBs, including *Bacillus*, *Enterobacter*, *Rhizobium*, *Acinetobacter*, and *Burkholderia*, emit hydrogen sulfide (H_2S) under anaerobic conditions. H_2S then reacts with ferric Phosphate to form soluble ferric acid. By a process known as chelation, many of the insoluble oxides of aluminum and iron are also formed by these organic acids (Moura *et al.*,2021). Nitrobacter and Curularia have shown the release of nitric and sulfuric acids to enable the dissolution of phosphorous. *Brassica iuncea's* elemental sulfur was converted into sulfate and thiosulfate by the sulfur-oxidizing bacteria Delftia. Many PSBs release 2-keto gluconic acid, a calcium chelator that can also be found in hydroxyapatite and aluminum phosphates (Buttrós *et al.*,2022). Other acids, such as humic and fulvic, are also useful chelators of Ca, Al, and Fe and are created during the microbiological breakdown of plant waste. Acids that react and stabilize with aluminum and iron while searching for fixing sites make chelates. The most important stabilization procedure is thought to be chelation.

The strongest calcium chelator secreted by PSBs is 2-ketogluconic acid. Such PSBs are used to solubilize fluorapatites, hydroxyapatites, and aluminum phosphates. An effective chelator of iron, aluminum, and calcium in insoluble phosphates, fulvic, and humic acids is released by plant detritus's microbial breakdown (Araújo *et al.*,2022). It is caused by the mineralization process in soil with a high concentration of phosphorus-containing organic molecules. Extracellular enzymes such as phytases, phospholipases, phosphoserines, and phosphodiesterases are produced by soil *bacillus* and *Streptomyces spp*. that mineralize very potent organic phosphates. In addition, microorganisms can solubilize insoluble Phosphorus, and hence most of the Phosphorus they incorporate in their growth; after their death, the previously insoluble nutrient returns to the soil in its soluble form. Thus, the immobilization process occurs mainly when fertilization is excess, and most of the nutrient is retained in metallic oxides and soil clay. This Phosphate is released into the environment during PSB mortality or under stressful conditions (Silva *et al.*, 2022). Microorganisms or other plants then absorb it to fulfill their phosphorus needs. The biochemical and physical-chemical characteristics mostly break down the organic phosphorus compounds. For instance, while phosphonates, phytic acid, and polyphosphates degrade slowly, sugar phosphates, nucleic acid, and phospholipids degrade easily. Weather conditions, particle size, and soil pH are only a few variables that affect microbial activity (Wieczorek *et al.*, 2022).

3 Phosphorus-Solubilizing Bacteria: Variety of Useful Functions

3.1 Role of P-solubilizing bacteria in crop improvement

Large numbers of chemical fertilizers are required to increase crop growth and yield. Many other tactics have emerged to remove environmental issues and the rising cost of various chemical fertilizers, for example, the use of healthy soil microbes (Kundu *et al.*,1984). Phosphorus-solubilizing microbes with various growth-regulating properties extract Phosphorus from a soil's poorly available sources. Hence, it is approved that screening of given phosphate solubilizing separates used as biofertilizers to enhance the growth or yield of the plant is of interest. These cold-harming P solubilizers have desirable traits like nitrogen fixation and anti-phytopathogen activity (Prakash *et al.*, 2019.

Additionally, PSBs support plant growth by enhancing nitrogen fixation efficiency through bio-inoculation testing (Arash *et al.*,2022). According to reports, GA and IAA synthesis has been linked to phosphate solubilization using *Pseudomonas sp.* and *Rhizobium leguminosarum* (Li *et al.*, 2021). The final product of cyanate (HCN) synthesis, antifungal metabolites, and antibiotics are often visible in PSBs. PSBs protect plants by keeping them away from phytopathogens. A variety of substances, including phosphatases, indole acetic acid, gibberellins, and several organic and mineral acids, are produced by PSB to improve crop development (Cécile *et al.*,2022).

Moreover, PSBs promote nutrient uptake, root development, soil acidification, nutrient availability, and plant resistance to disease and drought. Mutant strains of the soil isolate *A. chroococcum, Pantoea agglomerans*, were used to inoculate wheat cultivars, and numerous nitrogen, Phosphorus, and potassium uptakes were observed. *Tomer et al.* demonstrated that *Pantoea agglomeransas* and *Azotobacter chroococcum* are healthy in fixing nitrogen as well as participating in the release of various growth regulators or fungicidal substances, fungi solubilizing Phosphorus (Tomer *et al.*,2017). *In vitro* cultivation of these two microbes leads to biofilms and populated fungal mycelium formation. Biofilms enhanced the production of synthetic acids and nitrogen fixation, which consists of IAA compound synthesization. Wheat, Anthurium, Tea, and rice are used in evaluating the growth-regulating hormones. Biofilms form pseudo nodules and nodular structures (Larissa *et al.*,2021). *Bacillus* Bacterial inoculation of M-13 doesn't germinate sunflower or with Phosphorus, simulate the setting or kernel yield, chemical makeup of seeds, and filling effectiveness during certain field circumstances (Saima *et al.*,2020). The PSB applications significantly stimulate seed filling effectiveness, kernel willingness, and seed set or rate by decreasing husk percentage (15.24%) or increasing the concentration of seed nutrients. The properties of *Bacillus megatherium var. Phosphaticum,* Phosphorus solubilizing bacteria, mostly affects the presence or absence of various quantities of phosphorus fertilizer. (Xie *et al.,* 2022). All seed micro and macro-nutrients significantly increased due to the application of PSB.

In conclusion, it can be said that the properties of Phosphate solubilizing bacteria in the presence or absence of phosphate fertilizers result in an enhancement of kernel yield and embryo set to changes in the number of nutrients. It was studied to observe changes in sugarcane growth, yield, and soil-available Phosphorus. The properties of Phosphorus solubilizing bacteria stimulate the rhizosphere PSB group or attainability of soil phosphorus for plants. It increased stalk weight and group or resulted in a 12.6% increase in cane yield without application. Final results showed that Phosphorus solubilizing bacteria treatment positively impacted plant growth metrics such as nodulation and mycorrhizal colony. (Cécile *et al.,*2022). *Pseudomonas strains* GP70 GR1 could work as biofertilizers, lowering the need for chemical fertilization in peanut farms to form good results (Bang *et al.,*2019). The various effects of *Bacillus amyloliquefaciens CTC12* (KT633845) and *Burkholderia cepacain KHD08* (KT717633) with inorganic fertilizer (Ca-P) such as Al-P or Fe-P occluded in agricultural soil with acidity (Table 2). The overall application of 75% inculcated Phosphorus gives the most available Phosphorus (Tanushree *et al.,*2021). A single superphosphate and Phosphorus solubilizing bacteria influence grain phosphorus absorption and pod yield. This type of rhizobacteria showed a helpful effect as a biofertilizer, which combines with a small amount of inorganic phosphorus fertilizer to improve Phosphorus availability in soil and crop prolificity (Payam *et al.,*2022).

Table 2: Different roles of PSB in specific crops.

Microbial P-solubilizers	**Function**	**Crops**	**Reference**
Acetobacter awamorii, Pantoea. striata, and A. chroococcum	Intake of Nutrients Enhance the production	Wheat and rice	(Xiyang *et al.*, 2021)
Acetobacter chroococcum, P. fluorescens, A. agglomerans, and A. azospi-rillum,	1. Nitrogen fixation, nutrient uptake, and growth hormone synthesis 2. Production of Phytohormones from Indole Acetic Acid	Crops like wheat, maize, soybeans and *Citrus aurantium L.*	(Zhang *et al.,*2023)

Proteus mirabilis, Haloferax sp. IARI-MAAB2, P. aeruginosa	1. Colonization of non-legume plant roots by helpful microbes. 2. The biofilms formed when bacteria invaded fungal mycelia.	Anthurium, rice, wheat, and tea	(Yuan *et al.*,2017)
Pseudomonas jessenii MP-1, *Lysinibaccilusmacroides* ST-30	1. Enhanced seed sprouting efficiency 2. Synthesis of a wide variety of organic acids, including butyric, citric acid, keto gluconic malic, or succinic acid	*Haseolus vulgaris L.* (Himalayan red kidney bean), *Cicer arietinum L.* (chickpea), *Vigna radiata* (Mung bean), *Pisum sativum* (Pea), *Zea mays* (Corn)	(Moura *et al.*,2017)
M-13 Bacillus,	1. Increase germination rates, seed filling percentages, and nutrient absorption concentration.	*Helianthus annuus* L. (Sunflower)	(Liu *et al.*, 2020)
Sodium-Phosphate-Tolerant *Bacillus megatherium*	1. Increased sugar and juice production, 2. Accessible amount of P in the soil	*Saccharum officinarum L.* (Sugarcane)	(Abdelmoteleb *et al.*,2020)
Types of *Pseudomonades,* Including GR1, PP22, and GP70	1. Enhance legume production and development. 2. Using vitamin B, peanut trees can increase their yield and nutrient uptake.	Arachis hypogaea (peanut)	(Adnan *et al.*, 2020)
Bacteroides megaterium CS22 (Firmicutes), Pseudomonas frederiksbergensis	1. Enhanced rape's capacity to grow and absorb Phosphate.	*Brassica napus* (improved rape)	(Shen 2021; Li *et al.*,2020)

11-D3, Vibrio paradoxus 19-D4, and *Arthrobacter defluvii 06-OD12*	2. Increase of crop development and phosphorus absorption.		
CTC12 Bacillus amyloliquefaciens, CTC12 Bacillus amyloliquefaciens	1.Increase yield 2.To promote Growth	*Arachis hypogaea. L* (groundnut)	(Mosela *et al.*,2022)

3.2 Biological Leaching Processes Employ Phosphorus-Solubilizing Bacteria

The formation of the halo zone, which biologically leaches PSB's ability, is controlled by the liquid and agar media. *Acetobacter aceti* is regarded as one of the top PSB strains for its ability to dissolve Phosphate (Lucero *et al.*,2021). The generation of various organic acids appears beneficial from using *Pseudomonas aeruginosa* or *Aspergillus ficuum*. Some earth elements, such as thorium-uranium or Egyptian monazite, can be lixiviated with its help. Harvest of *P. aeruginosa*, 14 and 1 g/L of oxalic acid and citric acid, are produced from 6.3 g/L of 2-ketogluconic acid or *A. ficuum*. The maximum percentage of rare earth element's (REE) chemical leaching is about 0.6 %, uses roughly 1 g/L of oxalic acid, 14 g/L of citric acid, or 6 g/L of 2-ketogluconic acid (Qiao *et al.*,2019). The PSB strains like *Pseudomonas fluorescens*, *P. putida*, *P. rhizosphaerae*, *Mesorhizobium ciceri*, *Bacillus megaterium*, and *Acetobacter aceti* specified the biological leaching. Among them, *A. ceti* resulted in wider capability (Tang *et al.*,2020). While *P. rhizophaerae, A. aceti, Azospirillum lipoferum, and B. megaterium* prompted the leaching at different percentages of calcium, like 6 %, 7 %, or 32 %. The elements that can be bio-leached with PSB are shown in *Table 3*. Primary sources of REE are fluorocarbonate mineral, called bastanasite, and phosphate mineral, called monazite (Jiang *et al.*,2021). Mostly, 70% of rare earth metal oxides are present in monazite with a 10 to 40 % fraction of La_2O_3, 20 to 30 percent fraction of Ce_2O_3, and a considerable quantity of samarium, neodymium, and praseodymium. The amount of thorium is between 4 to 12 percent. In this activity, *P. putida*, *Paenibacillus azospirillum brasilense*, *Pseudomonas rhizophaerae*, *Paenibacillus polemi*, *P. fluorescens*, PSB strains, and *Bacillus megaterium* are excessively used (Table 3) (Timofeeva *et al.*,2022).

The leaching liquors of *A. aceti* were found to contain lanthanum (2.8 mg/L), cerium (5 mg/L), lanthanum, or both (0.005). Malic and acetic acids combine with lanthanum or cerium to form complexes. *P. rhizophaerae*, *A. brasilense*, and *A. lipoferum* are the causes. A complexation occurred when maleic acid or acetic acid was dissolved in water, or Re2O3 was present (Maharajan *et al.*, 2018).

Table 3. Bio Leaching of elements using Phosphate Solubilizing Bacteria (PSB)

Bioleaching Process of Various Elements	Lead and cadmium, two rare earth elements, leach out.	Calcium leaching	Cerium and lanthanum leaching	Th (thorium)and U (uranium) leaching	ZnCO3(calamine) and (Mg, Ni)$_3$Si$_4$O$_{10}$(OH)$_2$·nH$_2$O (garnierite) leaching
Strains of phosphorus-	*Bacillus megaterium,*	*Azospirillumlipoferum, Pseudomonas*	*Azospirillum aceti, A.*	*p. aeruginosa and A. ficuum*	*Bacillus and Pseudomonas*

solubilizing bacteria (PSB)	*Bacillus fluorescens, Pseudomonas putida, Pseudomonas rhizosphaerae, Acetobacter aceti, and Pseudomonas rhizosphaerae*	*rhizosphaerae, Bacteroides megaterium,*	*lipoferum, P. rhizosphaerae, Mycobacterium ciceri, and Mycobacterium rhizogenes*		
Organic Acid Synthesis	malic acid and acetic acid	acids like formic, acetic, and malic acid	Propionic acid, formic acid, acetic acid or gluconic acid	Acids the same as citric, oxalic, and 2-keto gluconic	citric acid
Reference	(Maharajan *et al.*, 2018)	(Nadeem *et al.*, 2023)	(Noman *et al.*, 2023)	(Akhtar *et al.*, 2023)	(He *et al.*,2021)

3.3 Using PSB to Help Plants Grow Under Stress Conditions

The characteristics and processes used to generate soil are greatly influenced by climate. Every region of the Earth's surface is experiencing a drastic change in the climate (Moseri *et al.*,2023). By the 21st century, the average temperature will rise by an additional 2-3°C. Nearly 30 to 40% of agricultural land has low productivity due to phosphorus deficiency (Alewell *et al.*, 2020). In acidic soil, different phosphate ions indissociably bond with alkaline phosphatase or fluorinated ethylene propylene (Nacoon *et al.*,2021). The further classifications that aid in the salinity stress include the *Agrobacterium* (4%), *Bacillus* (12.2%), *Flavobacterium* (3%), *Rhizobia* (17%), *Pseudomonas* (15%), *Burkholderia* (11.5%), *Flavobacterium* (6%), and *Erwinia* (10%) (Table 4) (Kim *et al.*,2021). Utilization of PSB for plant development under stress conditions is depicted in Figure 3. PSB can promote growth in various methods, including colonizing the root and producing ACC deaminase, PSB, axines, antibiotics, chitinase, or siderophores. Indole acetic acid, other mineral and organic acids, phosphatases, and gibberellins are all released by PSB to promote growth (68). Assimilation of water and nutrients, soil acidity, increased root growth, availability of nutrients, and resistance to disease and drought are all effects of PSB(Figure 3)(Sharma *et al.*,2020).

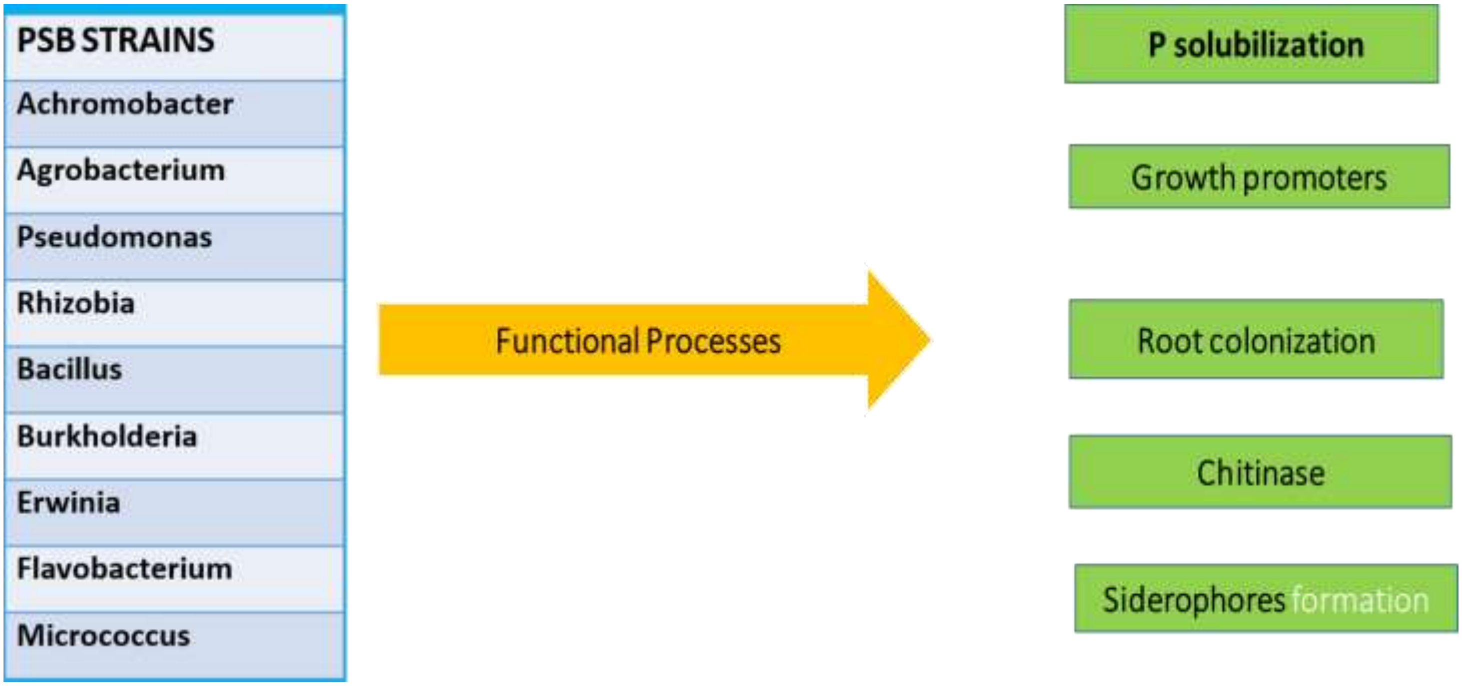


Figure 3: Utilization of PSB for Development of Plants During Stress Conditions (Sharma *et al.*,2020).

3.4 Use of PSB to immobilize various Heavy Metals

Heavy metals tolerant phosphate solubilizing bacteria (PSB) were separated and studied in polluted soil during the remediation of cadmium and lead (Kumar *et al.,* 2020). In many parts of the world, soil contamination caused by heavy metals has become a serious problem. Although enormous metal immersion in soil is rising due to human activities like ore mining, waste recycling, and sewage irrigation, heavy metals are naturally present in the Earth's crust. After examination, it became clear that the increase in soil microbial activity was caused by PSB's removal of heavy metals (Yahya *et al.*,2021).

Figure 4 shows how PSB is used to immobilize various heavy metals. (Boubekri *et al.*,2021). Lead ions are changed into pyromorphite or hydroxyapatite lead via the separation of L1–5. Future bioremediation of soil contaminated with lead may take advantage of PSB's abilities to immobilize lead (Prakash *et al.*,2019). It results from phosphate solubilization or biomineralization. Lead causes strong phosphate compounds to form in the soil, reducing the amount of bioavailable lead (Pirttilä *et al.*,2021). The effectiveness of PSB in immobilizing lead soil is investigated using pot trials, soil cultivation, or broth cultures (Figure 4) *(*Cheng *et al.*,2022).

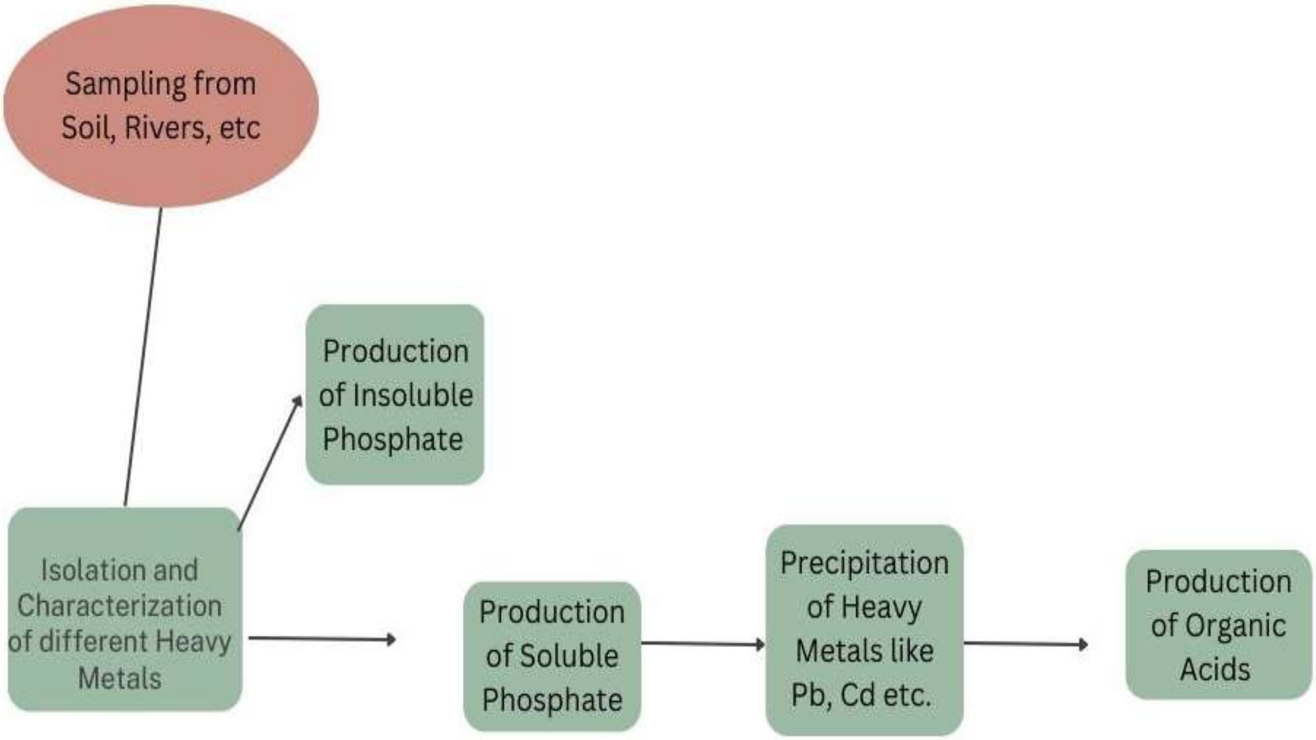


Figure 4: (Cheng et al.,2022) Application of PSB to immobilize different heavy metals and form organic acids.

Table 4. Demonstrates various PSB types in the immobilization of various heavy metals.

Strains of (PSBs)	**Sources**	**Important Role**	**References**
Enterobacter spp., Lactococcus spp and Bacillus spp.	Soiled soils	The dissolution of lead and cadmium ions	(Owen 2015; M *et al.*, 2020)
Pseudomonas putida and Leclercia adecarboxylata	Soil	To prevent lead (Pb) from leaching into the soil	(Jokkaew *et al.*,2022)
Plasmodium annatis HCR2 and Bacillus thuringiensis GL-1	Rocks made of Phosphate	phosphate rocks' ability to immobilize lead (Pb)	(Haoming *et al.*,2019)
P. ananatis and B. thuringiensis	Spoiled soils	Immobilization of lead (Pb) in phosphate minerals	(Zhengtao *et al.*,2018)

Acinetobacter, *Cupriavidus*) *Pseudomonas*, *Stenotrophomonas*, *Bacillus*, Ochrobactrum, *Arthrobacter*, and *Massilia*	Soil	immobilization of Pb (lead) in soil	(Wan *et al.*,2020)
Enterobacter aerogenes, Enterobacter taylorae and Enterobacter asburiae	River	In river Immobilization of Cd (cadmium)	(He *et al.*,2022)

Phosphate solubilizing bacteria's role in soil properties

Using chelating agents, soil pH reduction, and mineralization, *Pseudomonas*, *Bacillus*, and *Rhizobium* improve soil fertility. The pH of the soil is lowered by acid production (Tian *et al.*,2021). Mineral, microbial, and organic components comprise the three main parts of soil. Additionally, microorganisms as biofertilizers are being studied to combine the nutrients in the biological system and improve soil fertility (Alori *et al.*,2017). In addition to these microorganisms, Phosphate solubilizing bacteria (PSB) are primarily studied since they are used in crops and contribute to plant growth (Billah *et al.*,2019). The massive bacterial genus known as PSBs helps plants grow by giving them a set amount of nutrients, such as Phosphorus. PSB uses auxin, a hormone that controls growth and directly impacts plant development. Bacillus, Rhizobium, and Pseudomonas bacteria from the heterogeneous PSB group were found to improve soil fertility (McMahon *et al.*,2019). By combining inorganic Phosphate in the soil and improving plant bioavailability of P, these strains also contribute to crop growth, development, and production (Laakso *et al.*,2020). Different Phosphate solubilizing bacteria are the most helpful in biocontroling or biofertilizing agents. PSB shows a great range of biofertilizers spectrum (Hébert *et al.*,2019). Many active biofertilizers like *Bacillus circulans*, *Pseudomonas straita*, *Bacillus megaterium*, or *Bacillus subtilis* (Xu *et al.*,2020). When isolated, maize plants were contaminated to *Helminthosporium maydis*, beneficial biofertilizers (Gebrim *et al.*,2010). *Figure 5* depicts Phosphate Solubilizing Bacteria as a Biofertilizer for Increasing Soil Fertility. *Burkholderia cepacia*, on the other hand, breaks down tricalcium phosphate, which helps plants grow better (Rodriguez *et al.*,2006). The development of *Ralstonia solanacearum* in tomatoes reduces bacterial wilting. Chickpea biomass is increased by a relationship between *Piriformospora indica* and *Pseudomonas striata* (Babalola *et al.*,2012). *Pseudomonas fluorescens, Pseudomonas chlororaphis*, or *Bacillus cereus* cause plants' root, shoot, nitrogen, or phosphorus uptake to remodel (Mamta *et al.*,2010). Most studies have demonstrated through experimentation that Bacillus sp. increased the growth or harvesting of cotton (Tilahun *et al.*,2011).

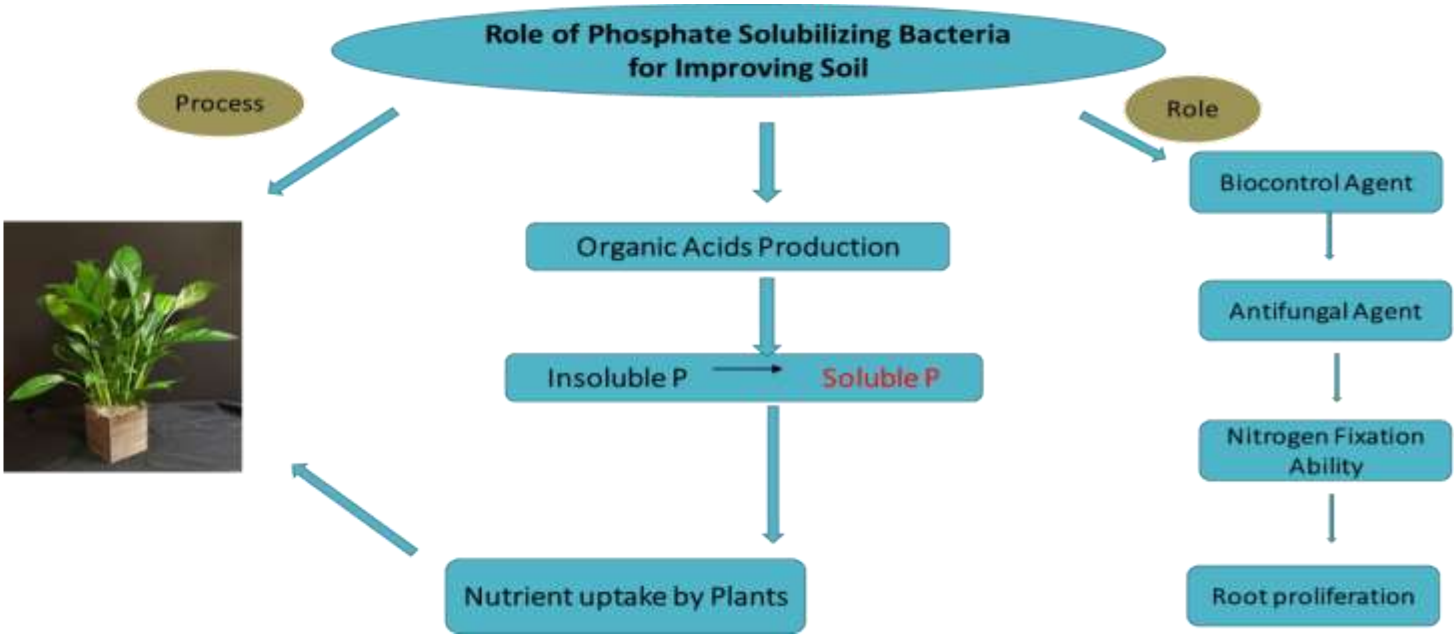


Figure 5: Phosphate Solubilizing Bacteria for Improving Soil Fertility as a Biofertilizer

3. Current Trends

PSB is gaining popularity as an alternative to chemical fertilizers in sustainable agriculture. It can solubilize the phosphate present in soil and make it available to plants, thus increasing crop yield. Researchers are focusing on isolating and developing novel strains of PSB that can solubilize phosphates more efficiently and survive under adverse environmental conditions. The formulation of PSB-based biofertilizers is gaining momentum, and several companies are commercializing these products for use in agriculture (Khan *et al.*, 2022). Recent research has shown that PSB can work more efficiently with other beneficial microbes. So, creating microbial consortiums, including PSB, is becoming more popular. The potential of PSB in the bioremediation of polluted soils and water bodies is also being investigated. Phosphates from organic and inorganic sources can be solubilized, making them available for microbial phosphate breakdown. Using molecular-based methods also creates new opportunities for measuring rhizosphere irritability and soil expression and detecting the presence or quantity of certain microorganisms. Basic primers depend on the protected region; for instance, they have been found in various bacteria connected to phosphate organization, including *Pseudomonas sp*. or mycorrhizal fungi.

5. Future Prospects

The PSB plays a significant role in agricultural practices and environmental remediation. These microbes convert insoluble Phosphate to soluble Phosphate, which plants more easily absorb. It boosts plant growth and productivity while reducing the need for synthetic fertilizers, which could have negative environmental implications. The prospect of PSB appears promising, given that scientists are looking into innovative strategies for increasing crop percentage through environmentally friendly plant-growth-promoting bacteria. Close cooperation between agronomists, fermentation experts, and soil microbiologists is required to use such bioproducts successfully. Doing more research and validating biotechnological plans developed in labs or greenhouses over protracted periods is important. The actions of multifunctional P solubilizers can be accepted as workable tools in environmental microbiology and sustainable agriculture.

6. Conclusion

Soil problems always worsen because Phosphorus is an essential element for plants, which is excellent for the environment and the economy. Unbalanced phosphorus addition to the soil, which lowers soil fertility, is a common problem. The phosphate-solubilizing bacteria, which is vital to agronomy and serves various functions, can significantly reduce the demand for the purchase and application of chemical fertilizers, utilizing PSB to support plant growth under pressure. PSBs can produce enzymes, organic acids, and chemicals, which help to facilitate the growth. With PSBs, heavy metals can be eliminated or immobilized. To ensure a sustainable agricultural environment, researchers must continue to learn about phosphate-solubilizing bacteria and share their results with farmers and stakeholders to improve crop yield for human beings.

Abbreviation

PSB: Phosphate Solubilizing Bacteria

P: Phosphorous

Fe: Iron

Al: Aluminum

ACC: 1-Aminocylopropane-1-carboxylic acid

IAA: Indole Acetic Acid

HPLC: High-Pressure Liquid Chromatography

LCMS: Liquid Chromatography Mass spectrometry

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Availability of data

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