



## **Role of Phosphate Solubilizing Microorganisms in Agriculture**

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### **Introduction**

Phosphorus (P) is one of the major growth-limiting macronutrients required for proper plant growth, particularly in tropical areas, due to its low availability in the soil (Kumar *et al.*, 2018). It accounts for between 0.2 and 0.8% of the dry weight of plants, and it is contained within nucleic acids, enzymes, coenzymes, nucleotides, and phospholipids. P is essential in every aspect of plant growth and development, from the molecular level to many physiological and biochemical plant activities including photosynthesis, development of roots, strengthening the stalks and stems, formation of flowers and seeds, crop maturity and quality of crop, energy production, storage and transfer reactions, root growth, cell division and enlargement, N fixation in legumes, resistance to plant diseases, transformation of sugar to starch, and transporting of the genetic traits. Adequate P availability is also required for laying down the primordia of plant reproductive parts during the early phases of plant development (Thakur *et al.*, 2014). Phosphorus is the second most important macronutrient required by the plants, next to nitrogen. Yet, the availability of soluble forms of P for plants in the soils is limited because of its fixation as insoluble phosphates of iron, aluminum, and calcium in the soil. Most soils possess considerable amounts of P, but a large proportion is bound to soil constituents. Soil with low total P can be supplemented with P fertilizer but are not able to hold the added P. About 75–90% of the added chemical P fertilizer is precipitated by metal cation complexes and rapidly becomes fixed in soils and has long-term impacts on the environment in terms of eutrophication, soil fertility depletion, and carbon footprint (Thakur *et al.*, 2014). Microorganisms are integral in the natural phosphorus cycle. The use of phosphate solubilizing microorganisms (PSMs) as biofertilizers for agriculture enhancement has been a subject of study for years.

### **Availability of Phosphorus in the Soil**

Phosphorus is a reactive element and does not exist as elemental form in the soil. Phosphorus in the soil solution exists as insoluble inorganic phosphorus and insoluble organic phosphorus. Its cycle in the biosphere can be described as “sedimentary,” because there is no interchange with the atmosphere, and unlike the case for nitrogen, no large atmospheric source can be made biologically available. Consequently, deficiency of phosphorus severely restricts the growth and yield of crops. The phosphorus level in the soil is about 0.05%. Soil test values are generally much higher, but the greater part of it, about 95 to 99%, is present in the form of insoluble phosphates. The concentration of soluble P in soil solution is usually



very low, normally at levels varying from ppb in very poor soils to 1 mg/L in heavily fertilized soils. Plant cell might take up several P forms, but the greatest part is absorbed in the forms of phosphate anions mainly  $\text{HPO}_4^{2-}$  or  $\text{H}_2\text{PO}_4^-$  depending upon soil pH. The main input of inorganic P in agricultural soil is applying phosphorus fertilizers. Nearly, 70 to 90% of phosphorus fertilizers applied to soils is fixed by cations and converted inorganic P. P gets immobilized by cations such as  $\text{Ca}^{2+}$  in calcareous or normal soils to form a complex calcium phosphate ( $\text{Ca}_3(\text{PO}_4)_2$ ) and with  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$  in acidic soils to form aluminum phosphate (AlPO) and ferrous phosphate (FePO). These are insoluble forms and consequently unavailable. These accumulated phosphates in agricultural soils are adequate to maintain maximum crop yields worldwide for about 100 years if it could be mobilized, converted into soluble P forms using of PSM. A greater concern has, therefore, been made to get an alternative system yet low-priced technology that could supply adequate P to plants.

**Diversity of Phosphate Solubilizing Microorganisms**

Phosphate solubilizing microorganisms (PSMs) are group of beneficial microorganisms capable of hydrolyzing organic and inorganic phosphorus compounds from insoluble compounds. Among these PSMs, strains from bacterial genera (*Bacillus*, *Pseudomonas*, and *Rhizobium*), fungal genera (*Penicillium* and *Aspergillus*), actinomycetes, and arbuscular mycorrhizal (AM) are notable (Table 1). Soil is a natural basal media for microbial growth. Mostly, one gram of fertile soil contains 101 to 1010 bacteria, and their live weight may exceed 2,000 kg ha<sup>-1</sup> (Thakur *et al.*, 2014). Among the whole microbial population in soil P, solubilizing bacteria comprise 1–50% and P solubilizing fungi 0.1 to 0.5% of the total respective population. PSMs are ubiquitous, and their figures differ from soil to soil. Most PSMs were isolated from the rhizosphere of various plants, where they are known to be metabolically more active. Apart from those species, symbiotic nitrogenous rhizobia and nematofungus *Arthrobotrys oligospora* have also shown phosphate solubilizing activity.

**Table 1:** Potential P solubilizing microorganisms.

Microbes	PSMs
Bacteria	<i>Bacillus megaterium</i> <i>Bacillus pulvifaciens</i> <i>Bacillus coagulans</i> <i>B. chitinolyticus</i> <i>Bacillus sircalmous</i> <i>Thiobacillus ferrooxidans</i> <i>Pseudomonas canescens</i> <i>Pseudomonas putida</i> <i>Pseudomonas fluorescens</i> <i>Pseudomonas striata.</i> <i>Rhizobium meliloti</i> <i>Rhizobium leguminosarum</i>
Fungi	<i>Aspergillus nNiger</i>



	<i>Aspergillus clavatus</i> <i>Aspergillus awamori</i> <i>Aspergillus candidus</i> ; <i>A. parasiticus</i> ; <i>Aspergillus fumigatus</i> ; <i>A. rugulosus</i> <i>Aspergillus flavus</i> <i>Penicillium bilaii</i> <i>Penicillium citrinum</i>
Actinomycetes	<i>Acinetobacter rhizosphaerae</i> [ <i>Streptomyces albus</i> ; <i>S. cyaneus</i> ; <i>Streptoverticillium</i>
Cyanobacteria	<i>Calothrix braunii</i>

### Mechanism of P Solubilization

PSMs apply various approaches to make phosphorus accessible for plants to absorb. These include lowering soil PH, chelation, and mineralization.

#### 1. Lowering Soil pH.

The principal mechanism for solubilization of soil P is lowering of soil pH by microbial production of organic acids or the release of protons. In alkaline soils, phosphate can precipitate to form calcium phosphates, including rock phosphate (fluorapatite and francolite), which are insoluble in soil. Their solubility increases with decreases in soil pH. PSMs increase P availability by producing organic acids that lowers the soil pH (Kumar *et al.*, 2018). Strong positive correlation has been reported between solubilization index and organic acids produced. PSMs are also known to create acidity by evolution of CO<sub>2</sub>, as observed in solubilization of calcium phosphates. Production of organic acid coupled with the decrease of the pH by the action of microorganisms resulted in P solubilization. As the soil pH increases, the divalent and trivalent forms of inorganic P, HPO<sub>4</sub><sup>-2</sup> and HPO<sub>4</sub><sup>-3</sup>, occur in the soil. The PSMs may release several organic acids (Table 2). These organic acids are the products of the microbial metabolism, mostly by oxidative respiration or by fermentation when glucose is used as carbon source. The type and amount of organic acid produced differ with different organisms. Efficiency of solubilization is dependent upon the strength and nature of acids. Moreover, tri- and dicarboxylic acids are more effective as compared to monobasic and aromatic acids, and aliphatic acids are also found to be more effective in phosphate solubilization compared to phenolic, citric, and fumaric acids.

**Table 2:** Diversity of organic acid produced by PSMES.

PSM isolates	Organic acids
<i>Bacillus</i> sp.	Citric acid, malic acid, succinic acid, fumaric acid, tartaric acid, gluconic acid
<i>Pseudomonas</i>	Citric acid, succinic acid, fumaric acid, gluconic acid, 2-ketogluconic acids
<i>Proteus</i> sp.	Citric acid, succinic acid, fumaric acid, gluconic acid
<i>Aspergillus</i>	Citric acid, gluconic acid, oxalic acid, succinic acid,



	malic acid, glycolic acid
<i>Azospirillum</i> sp.	Citric acid, succinic acid, fumaric acid, gluconic acid
<i>Penicillium</i> sp.	Gluconic acid, glycolic acid, succinic acid, malic acid, oxalic acid, citric acid

**2. Chelation**

Organic and inorganic acids produced by PSM dissolve the insoluble soil phosphates by chelation of cations and competing with phosphate for adsorption sites in the soil. The hydroxyl and carboxyl groups of the acids chelate the cations bound to phosphate, thereby converting it into soluble forms. These acids may compete for fixation sites of Al and Fe insoluble oxides, on reacting with them, stabilize them, and are called “chelates”. 2-ketogluconic acid is a powerful chelator of calcium. Production of inorganic acids, such as sulphidric, nitric, and carbonic acid, has been reported. Nitric and sulphuric acids react with calcium phosphate and convert them into soluble forms.

**3. Mineralization**

The other mechanism of solubilizing soil P is mineralization. Organic phosphate is transformed into utilizable form by PSM through process of mineralization, and it occurs in soil at the expense of plant and animal remains, which contain a large amount of organic phosphorus compounds such as nucleic acids, phospholipids, sugar phosphates, phytic acid, polyphosphates, and phosphonates. Mineralization and immobilization of soil organic P plays a vital role in phosphorus cycling of the agricultural land. PSMs mineralize soil organic P by the production of phosphatases like phytase that hydrolyze organic forms of phosphate compounds, thereby releasing inorganic phosphorus that will be immobilized by plants. Alkaline and acid phosphatases use organic phosphate as a substrate to convert it into inorganic form. The following are among the commonly reported phytase producing fungus: *Aspergillus candidus*, *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus parasiticus*, *Aspergillus rugulosus*, *Aspergillus terreus*, *Penicillium rubrum*, *Penicillium simplicissimum*, *Pseudeurotium zonatum*, *Trichoderma harzianum*, and *Trichoderma viride*. Soil *Bacillus* and *streptomyces* spp. are able to mineralize complex organic phosphates through production of extracellular enzymes like phosphoesterases, phosphodiesterases, phytases, and phospholipases. Mixed cultures of PSMs (*Bacillus*, *Streptomyces*, and *Pseudomonas*) are most effective in mineralizing organic phosphate. Some PSM produces siderophores, hydrolyze the organic P in the soil resulting in P availability

**Mode of Plant Growth Promotion by PSM**

PSM exhibited the capacity to restore the productivity of degraded slightly productive and unproductive agricultural soils. The primary means by which PSM enhance plant growth is by improving P acquisition efficiency of plants, thereby converting of the insoluble forms of P to an accessible form (orthophosphate) by plants, an essential quality of PSMs. Inoculation of PSMs in soil or seed is known to enhance solubilization of applied and fixed phosphates in soil, resulting in better crop yield. It has also been reported that PSM help to absorb the phosphorus from a wider area by developing an extended network around the root system. As a result, these microbial communities when employed singly or in combination



with other rhizospheric microorganisms have shown considerable outcomes on plants in conventional agronomic soils. Inoculation with PSB such as *Pseudomonas*, *Bacillus*, *Rhizobium*, *Micrococcus*, *Flavobacterium*, *Achromobacter*, *Erwinia*, and *Agrobacterium* has been reported in increasing solubilization of fixed P ensuring high crop yields. PSMs promote plant growth via generating phytohormones, such as auxins, gibberellins, cytokinins, or polyamides. Organic acids such as carboxylic, glycolic, malonic, succinic, fumaric, and alpha-ketoglutaric acid that hasten the maturity and thereby enhance the ratio of straw as well as the total yield have also been recognized among phosphate solubilizers. Besides, the PSMs also facilitate plant growth by promoting the efficiency of nitrogen fixation through bioinoculation trials. Thus, production of IAA and GA coupled with phosphate solubilization by *Rhizobium leguminosarum* and *Pseudomonas* sp. (54RB) has been reported. PSMs also protect plants by avoiding phytopathogens, typically owing to the production of antibiotics, hydrogen cyanate (HCN), and antifungal metabolites.

### ***Trend of PSM Use as Biofertilizer and the Feature Prospect***

Phosphorus use efficiency in agricultural lands can be improved through inoculation of PSM. Indications of their contribution in solubilization of inorganic phosphates and mineral phosphates were reported. Ghaderi *et al.* (2008) demonstrated that the rate of P released by *Pseudomonas putida*, *Pseudomonas fluorescens* CHAO, and *Tabriz Pseudomonas fluorescens* was 51, 29, and 62%, respectively. Similarly, the inoculation of *Glomus fasciculatum* and *Azotobacter* resulted in significant improvement in uptake of P, K, and N through mulberry leaf as compared to the uninoculated plants. Likewise, improved phosphorus uptake and increased grain yield of wheat were reported following inoculation of phosphate solubilizing *Pseudomonas* and *Bacillus* species. PSM increases the availability of P without disturbing the biochemical composition of the soil. PSM can be used for various crops and not host specific. Several studies reported that the use of PSM enhanced growth, yield, and quality in many crops including walnut, apple, maize, rice, mustard, oil palm, aubergine and chili, soybean, wheat, sugar beet, sugarcane, chickpea, peanut and legumes, and potatoes (Table 3). PSMs have shown to enhance P uptake, the growth, and the yield when applied to crop plants. Adequate supply of P helps in seed formation and early maturation of crops like cereals and legumes (Kumar *et al.*, 2018). It causes early ripening and stimulates young plants to produce deeper and abundant roots. PSM improved sugarcane yield by 12.6%, and wheat yield up to 30% with *Azotobacter* inoculation and up to 43% with *Bacillus* inoculants [9] have been documented. Similarly, a 10–20% yield increase was reported in field trials using a combination of *Bacillus megaterium* and *Azotobacter chroococcum*. However, *Azospirillum* spp. showed increased yield in maize, sorghum, and wheat while *Bacillus* spp. revealed increased yield in peanut, potato, sorghum, and wheat.



**Table 3:** Effect of PSM on growth and yield performance of different crops

PSMs	Host plant
<i>Azotobacter</i>	Wheat
<i>Azotobacter chroococcum</i>	Wheat
<i>Azospirillum</i> spp.	Maize, sorghum, and wheat
<i>Bacillus</i>	Peanut, potato, sorghum, and wheat
<i>Pseudomonas</i>	<i>Zea mays</i> L., soyabean, Peanut
<i>Pseudomonas putida</i> and <i>Pseudomonas fluorescens</i>	Potato, radishes, rice, sugar beet, tomato, lettuce, apple, citrus, beans, ornamental plants, and wheat

### Conclusion

Application of PSM by inoculating in soil appears to be an efficient way to convert the insoluble P compounds to plant available P form, resulting in better plant growth, crop yield, and quality. *Bacillus*, *Pseudomonas*, *Rhizobium*, *Aspergillus*, *Penicillium*, and AMR are the most efficient P solubilizers for increasing bioavailability of P in soil. PSM provokes immediate plant growth by providing easily absorbable P form and production of plant growth hormones such as IAA and GA. Furthermore, PSM supports plant growth through production of siderophore and increases efficiency of nitrogen fixation. Besides, PSM acts as a biocontrol against plant pathogens via production of antibiotics, hydrogen cyanate (HCN), and antifungal metabolites. Thus, PSMs represent potential substitutes for inorganic phosphate fertilizers to meet the P demands of plants, improving yield in sustainable agriculture.

### References

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