ROLE OF PHOSPHATE-SOLUBILIZING MICROORGANISMS (PSMs) IN SUSTAINABLE CROP PRODUCTION

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Phosphorus (P), after nitrogen, is considered the most limiting macronutrient in most Indian soils. One of the most critical roles of P in plants is the storage and transfer of energy produced during processes like photosynthesis, which is later utilized during the growth and reproductive stages. Adequate P levels promote root development and hardiness, enhance tillering, and accelerate crop maturity. Soil test values for P serve as important indicators of P cycling in soils and considered an index for predicting crop response to P fertilization. However, utilization efficiency of applied P by crops mostly ranges from 15 to 30 % (Beura et al., 2022). The remaining portion contributes to the residual soil P pool and is not readily lost, except through erosion or runoff.

The low availability of P in Indian soils is largely due to its affinity to get fixed (to an extent of 60 to 70%) by calcium carbonate in alkaline and calcareous soils, and by iron and aluminium hydroxides in acidic (Patel et al., 2024). This reduced availability of P is a major constraint in achieving optimum yield for many crops including rice.

Since most of the phosphate fertilisers are imported, they place a significant burden on the foreign exchange reserves of the country. Moreover, their high cost makes them unaffordable for many Indian farmers with small holdings and limited resources. P mineral resources are finite and non-renewable; hence, their optimal, efficient and equitable use is essential to keep agriculture sustainable for the future generation.

PHOSPHORUS NUTRITION THROUGH PSMs

P nutrition in crops can be enhanced significantly through microbial inoculants like phosphate-solubilizing microorganisms (PSMs). These non-pathogenic soil microbes colonize the rhizosphere and convert insoluble P into available forms by different mechanisms. They also have plant growth-promoting characteristics and produce vitamins and phytohormones to improve plant root growth and increase nutrient uptake.

PSMs play an important role in supplementing P to the plants, promoting the sustainable use of phosphate fertilizers. These microorganisms are involved in several process that influence the transformation of soil P, making them an integral to the soil P cycle. Mechanisms such as lowering of soil pH through acid production, ion chelation, exchange reactions in growth environment etc. contribute to the phosphate solubilization by PSMs.

A wide range of microorganisms including bacteria, fungi, actinomycetes, and algae exhibit phosphate solubilization and mineralization capabilities:

Soil bacteria: *Pseudomonas spp.*, *Agrobacterium spp.*, *Bacillus spp.*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Thiobacillus*, among others.

Fungi: *Achrothcium*, *Alternaria*, *Arthrobotrys*, *Aspergillus*, *Cephalosporium*, *Cladosporium*, *Curvularia*, *Cunninghamella*, *Chaetomium*, *Fusarium*, *Glomus*, *Helminthosporium*, etc.

Actinomycetes: About 20% of actinomycetes, including *Actinomyces*, *Micromonospora*, and *Streptomyces*, are capable of P solubilization.

Algae: Cyanobacteria also reported to have P-solubilizing abilities.

Soil fungi, with their ability to travel long distances in soil than bacteria, may play important role in the P-solubilization as they produce higher quantities of organic acids like gluconic, citric, lactic, 2-ketogluconic, oxalic, tartaric and acetic acids.

Phosphate-Solubilizing Bacteria (PSB)

In the rhizosphere, a large number of plant-growth promoting rhizobacteria (PGPR), particularly PSBs, is known to promote plant growth and enhance plant productivity. These bacteria convert insoluble P into bioavailable forms. Most identified PSBs belong to the genera *Pseudomonas, Bacillus, Mycobacterium*, and *Enterobacter* (Hanif et al., 2015). Two main P-solubilization mechanisms of PSBs (Figure 1) are release of organic acids (e.g., malic, lactic, acetic, citric, and succinic acids) to dissolve insoluble P (RodríGuez and Fraga, 1999) and secretion of enzymes to degrade insoluble P compounds. Some PSBs produce phytohormones such as indole acetic acid (IAA), gibberellins (GAs) (Babu et al., 2015).

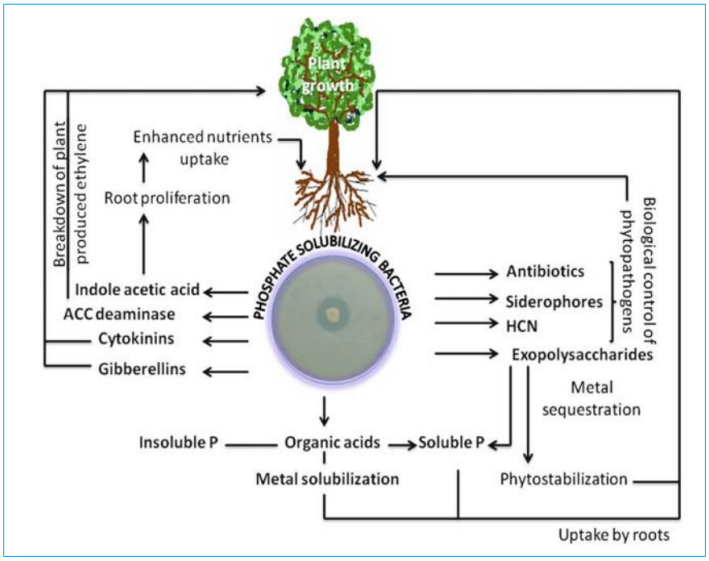

Figure 1. Plant growth promotion mechanism of phosphate-solubilizing bacteria (Source: Zaidi et al, 2009)

Ability of PSBs to colonize in rhizosphere significantly influences their efficiency in P solubilization and plant growth promotion (Ramachandran et al., 2007). Although many studies have been conducted on PSB isolation further research is required to understand more on their colonization behaviour, survival patterns, and P-dissolution mechanism.

PSBs secrete organic acids (Figure 2) of low molecular weight such as gluconic acid, fumaric acid and keto-gluconic acid, which solubilize P minerals and mobilize P for the crop uptake (He et al., 2002).

Arbuscular Mycorrhizal Fungi (AMF)

AMF characteristically colonize the roots of host plants and facilitate the promotion of plant growth through enhancing soil nutrient availability. They support plants by protecting them from pathogens and impart drought tolerance. By colonizing in roots, AMF improve plant nutrient uptake particularly P and hence contribute significantly to P nutrition (LiSmith and Read, 2008). AMF can partially substitute fertilizers as they can enhance nutrient availability in nutrient-poor soils and their role in mobilizing sparingly soluble P forms is valuable to enhance P nutrition to plants (Beura et al., 2022).

AMF synthesize organic compounds like siderophores, which facilitate the desorption of P into labile pools within the soil. Also, by producing organic acids, AMF solubilize partially soluble or insoluble P sources that are part of the crystalline mineral matrix in soils. Organic exudates like citrates, when released into rhizosphere, are particularly effective in enhancing P availability by mobilizing the less soluble forms of iron and aluminum bound phosphates or fixed P to insoluble calcium phosphates.

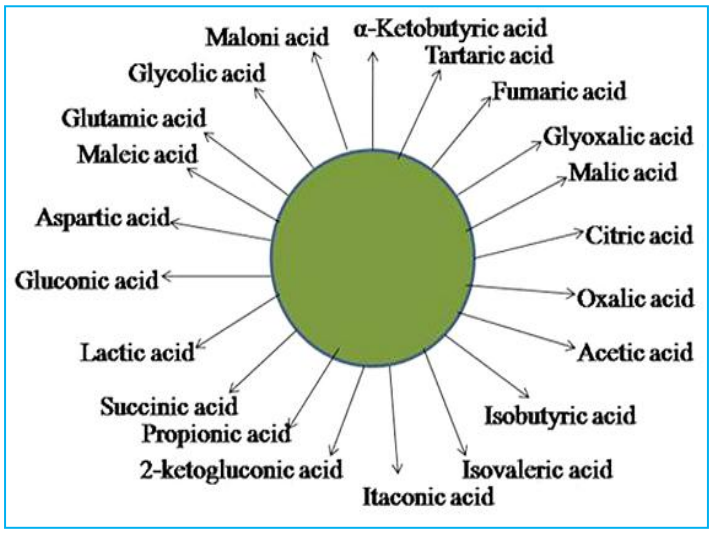

Figure 2. A schematic representation of organic acids produced by PSMs to solubilize inorganic forms of phosphate (Source: https://www.frontiersin.org/journals/micro-biology/articles/10.3389/fmicb.2017.00971/full)

MECHANISMS OF P SOLUBILIZATION

a) Lowering of soil pH and chelation

- The solubility of calcium phosphates is highest around pH 7.2.
- Organic acid excretion lowers pH, acidifying the microbial surroundings and releasing P ions through H^+ substitution for Ca^{2+}.
- Gluconic acid is the most frequently reported solubilizing agent, chelating cations bound to phosphate.
- Gram-negative bacteria often oxidize glucose directly to gluconic acid to solubilize phosphate.

b) Mineralization

- Many soil microbes produce phosphatase enzymes that mineralize organic phosphorus compounds into inorganic phosphate.
- This process parallels the mineralization of organic nitrogen.

c) Solubilization

- Microbial production of organic and inorganic acids solubilizes inorganic phosphorus compounds.
- Fungi like Aspergillus, Penicillium, and Fusarium are prominent acid producers, followed by bacteria such as Bacillus, Pseudomonas, Micrococcus, and Flavobacterium.

CONCLUSION

Phosphate-solubilizing microorganisms have tremendous potential as Bio-fertilizers. Mobilizing soil inorganic phosphate and increasing its bioavailability for plant use by harnessing soil PSM promotes sustainable agriculture, improves the fertility of the soil, and hence increases crop productivity. The use of PSM as microbial inoculants is a new horizon for better plant productivity. PSM technology can contribute to low-input farming systems and a cleaner environment. However, there is need to develop PSB technologies specific to various regions and this should be communicated to farmers in a relatively short time.

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