

Biological interventions to improve P-use efficiency and sustainable crop production

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With increase in food grain production in India from 50.8 million tonnes in 1950-51 to 241.57 million tonnes in 2010-2011, the production and consumption of phosphorus fertilizer has also increased from 9.8 thousand tonnes in 1950-51 to 4371 thousand tonnes in 2010-2011 and from 6.9 thousand tonnes in 1950-51 to 8,049 thousand tonnes in 2010-2011, respectively. Phosphorus is the second important primary nutrient element after nitrogen. Phosphorus is the least mobile major nutrient in soils and the prime limiting factor for plant growth.

Key words: Micro-organism, Phosphorus, Root, Soil

THOUGH phosphorus is present in soil in large amount, only 1 to 5% of it remains in plant-available form. Phosphorus (P) in soil exists predominantly in inorganic fractions that are either adsorbed to soil mineral surfaces or sparingly available precipitates, and in organic forms that are either adsorbed, incorporated within biomass, or associated with soil organic matter. Low P use efficiency is a significant challenge for agricultural production on P-deficient soil as well as in acidic and calcareous soils. Biological intervention directly or indirectly enhance the P-use efficiency with ecofriendly manner which helps to attain sustainable crop production. Different plant and microbial mechanisms increases bioavailability of soil native P as well as applied P in rhizosphere (Fig. 1).

Plant interventions

Two strategies by which plants may improve P-use efficiency are: (i) Root-foraging strategies that improve P acquisition by lowering the critical P requirement of plant growth and allowing agriculture to operate at lower levels of soil P; (ii) P-mining strategies to enhance the desorption, solubilisation or mineralization of P

from sparingly-available sources in soil using root exudates (organic anions, phosphatases).

P acquisition

In P acquisition, the most important traits are root morphological characteristics and architecture. P availability is unevenly distributed through the soil profile. Root architecture determines the extent of root exploration throughout the soil profile. Root architectural parameters, branching angle of basal roots and number of lateral branching per cm root, are positively

related to P efficiency. In most natural soils, P availability is greater in surface and near surface horizons than in sub soil, principally because of continually deposition of P onto the soil surface in senescent leaf and other plant residues. Hence root architectural traits that enhance the exploration and exploitation of surface horizons may therefore enhance P acquisition. In response to low P condition plant root changes its architecture. Deficiency of P induces more aerenchyma in adventitious roots, which may be a mechanism of reducing the metabolic

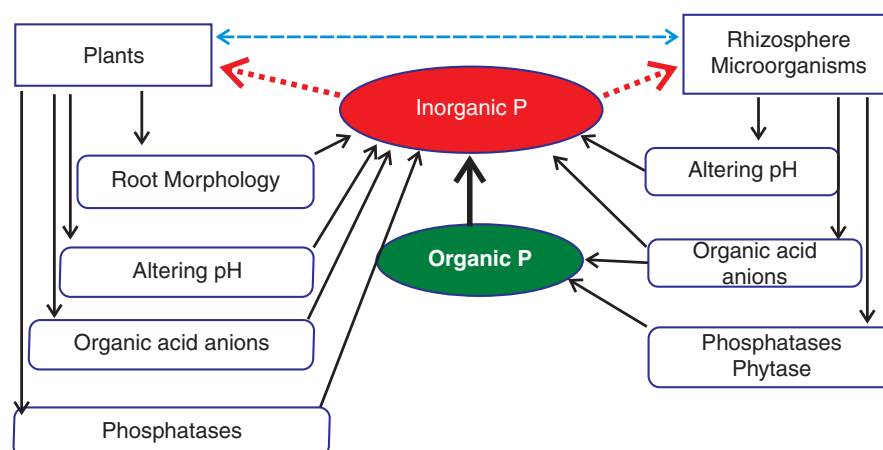


Fig. 1 Plant and Microbial mechanisms increasing bioavailability of soil native P as well as applied P in rhizosphere

Source: Rengel and Maschner, 2005, modified.

costs of soil exploration, shallower root, more dispersed laterals, which increases greater foraging area, more taproot laterals, longer and denser hairs of basal roots. All these changes lead to more exploration of surface soil and there is greater bioavailability of P.

P-mining strategies

Change in pH of rhizosphere

The speciation of P, i.e., the distribution of P among various species in solution is first of all determined by solution pH. Plant adsorbs either H_2PO_4^- or HPO_4^{2-} forms depending upon soil pH. These two species of P remain in amount in soil solution at pH above 7.2. Inorganic P in solution, not adsorbed by root or immobilized by micro-organism, can be adsorbed to mineral surfaces or precipitated as secondary P compounds. There are different mechanisms by which pH of rhizosphere changes making P available for plant uptake they are:

- Production of CO_2 and hence H_2CO_3 in rhizosphere by root and microbial respiration
- Root ion exchange
- Nitrogen fixation by rhizobium-legume symbiosis
- Change in redox potential of rhizosphere
- Organic matter decomposition
- Deficiency of P and Fe in soil.

Root exudates

Root exudation of various chemical molecules into the rhizosphere is largely dependent on the nutritional status of the plant, with some species exuding organic acid anions in responses of Al toxicity, P and Fe deficiency. Among root exudates, citric and malic acids are the most frequently involved in such a response of plant roots to P starvation. The composition of root exudates are very complex, and often ranges from mucilage, root border cells, extracellular enzymes, simple and complex sugars, phenolics, amino acids, vitamins, organic acids, nitrogenous macromolecules such as purines and nucleosides to inorganic or gaseous molecules such as HCO_3^- , OH^- , H^+ , CO_2 and H_2 . There are

Table 1. Function of root exudates

Component	Rhizosphere function
Phenolics	nutrient source, chemo attractant signals to microbes, microbial growth promoters, chelators of poorly soluble mineral nutrient
Organic acids	nutrient source, chemo attractant signals to microbes, chelators of poorly soluble mineral nutrients
Amino acids and phytosiderophores	nutrient source, chelators of poorly soluble mineral nutrients, chemo attractant signals to microbes
Vitamins	promoters of plant and microbial growth, nutrient source
Purines	nutrient source
Enzymes	catalysts for P release from organic molecules, biocatalysts for organic matter transformation in soil
Root border cells	stimulate microbial growth, release chemo attractants

various functions of root exudates also, which directly or indirectly help in P acquisition by plant (Table 1). Similarly different plants also release various kinds of organic anions (Table 2). Main mechanism of solubilization of soil inorganic P by citrate is, (i) the chelation of metals involved in the precipitation of P ions, and (ii) the formation of a soluble citrate-metal-P complex and up to some extent by ligand exchange reaction. Among organic acids efficiency of individual organic acids to mobilize P depend upon number of carboxylic group they possess and follow the series- tricarboxylic (e.g. citrate) > dicarboxylic (e.g. malate) > monocarboxylic acid. Phenolics make Fe and P available by forming relatively stable chelates with Fe and Al present in insoluble Fe- and Al-phosphates thereby increasing the solubility of Fe and P for plant uptake.

Micro-organism interventions

The central role of the microbial biomass in the cycling of P in soil has received increased recognition in recent years. P held within soil micro-organisms constitutes a significant component of the total soil P and is generally equivalent to, or exceeds that held in plant biomass. Microbial P in bulk soil, while highly variable, is estimated to typically account for around 2% to 10% of total soil P, although at different stages of soil development and within litter layers (soil surface) this may be as much as 50%. Importantly, microbial P is a highly dynamic pool of soil P and is subject to significant change in response to environmental factors such as soil temperature, moisture,

and carbon (C) availability. Micro-organisms decompose organic amendments added to soil (e.g. manures, plant residues) and mineralize organic P along with that of soil organic matter. In contrast micro-organisms also immobilize plant available form of P from soil solution (Fig 2).

P-solubilizing micro-organisms

Micro-organisms are integral to the soil P cycle and as such play an important role in mediating the availability of P to plants. Many microbial species have the capacity to solubilize sparingly soluble P *in vitro*. Inoculation with effective P solubilizers may increase P uptake and growth of plants. However, it is often not clear whether the improved P uptake by plants is directly attributable to P solubilization by the introduced microbe. Among the whole microbial population in soil, phosphorus solubilizing bacteria (PSB) constitute 1 to 50%, while phosphorus solubilizing fungi (PSF) are only 0.1 to 0.5% in P solubilization potential. Generally bacteria are more effective in P solubilization than fungi. Strains from bacterial genera *Pseudomonas*, *Bacillus*, *Rhizobium* and *Enterobacter* along with *Penicillium* and *Aspergillus* fungi are the most powerful P solubilizers.

Table 2. Dominant organic acid released by different plant

Plant species	Organic anion released (Dominant)
White lupin, Alfalfa	Citric acid
Maize, Wheat, Oilseed rape, Tomato	Malic acid
Sugar beet	Oxalic acid

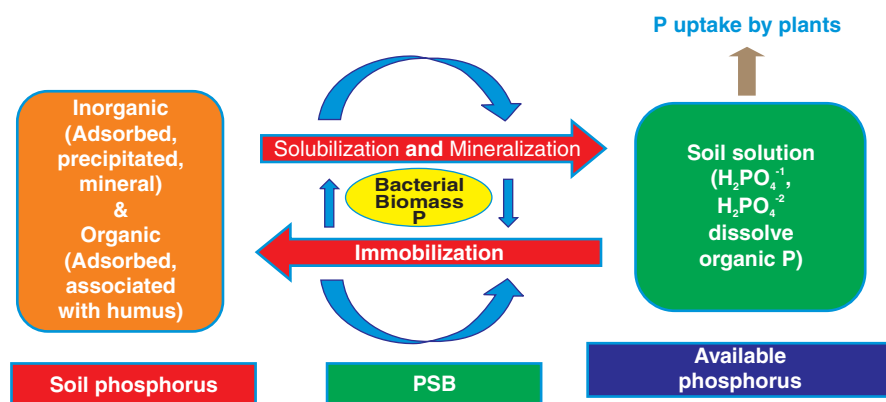


Fig. 2. Schematic representation of the importance of microorganisms to P availability in soil
Source: Richardson *et al.*, 2009, modified.

Both inorganic and organic form of P is made available to plant uptake by P solubilizing micro-organisms (PSM). Mechanisms for inorganic P solubilization by PSRB (P solubilizing rhizobacteria), are (i) release of organic and inorganic acids, and (ii) excretion of protons that accompanies to the NH_4^+ assimilation. The hydroxyl and carboxyl groups of acids chelate cations (Al, Fe, Ca) and decrease the pH in alkaline soils. P desorption potential of different carboxylic anions are *in the order: citrate > oxalate > malonate / malate > tartrate > lactate > gluconate > acetate > formate*.

Mycorrhiza association

Mycorrhizal symbioses are found in almost all ecosystems and can enhance plant growth through a number of processes which include improvement of plant establishment, increased nutrient uptake (particularly P and essential

micronutrients such as Zn and Cu). It is also well established that mycorrhizal fungi contribute significantly to the P nutrition of plants, particularly under low P conditions. Micorrhiza increase the bioavailability of soil P through different mechanisms, they are:

- Fungal hyphae release exudates, which solubilizes more P than root exudates alone
- Mycelium of arbuscular mycorrhiza excretes phosphatases, which potentially enhances the mineralization and utilization of organic P
- Root system of plant extends through extra-radical mycelia that increases the volume of soil explored up to several cm away from the root and then subsequently transferred to the plant
- High mycorrhizal hyphae density provides considerably greater surface area for the absorption of orthophosphate by plants and due

to the smaller size of hyphae in relation to roots and root hairs and their greater length relative to root hairs, hyphae are also most effective in exploiting soil pores and nutrient patches that may not be directly accessible to roots, and

- There is faster inflow of phosphate through external hyphae (approximately 1000-fold) than phosphate diffusion rate through soil.

SUMMARY

In the recent years, soil degradation is a big challenge for Indian agriculture as well as whole world due to heavy use of chemical fertilizers. Low P-use efficiency is another challenge for agriculture system to maintain sustainable crop production. Biological interventions are directly or indirectly enhance the P-use efficiency with ecofriendly manner. Micro-organisms are very efficient sources for enhancing the P-use efficiency. An obvious concern with the introduction of P-mining practices or more P-efficient crop genotypes is the possibility of soil mining and gradual depletion of soil fertility, especially in low input systems. This is probably less of a problem where novel genotypes are being introduced as part of a wider scheme to reduce P-removals and to protect the sustainability of the production system.

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