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Strategies and methods for improving phosphorus acquisition and its use efficiency: A review

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ABSTRACT

Phosphorus (P) is considered an essential nutrient for all and is also essential from global food security point of view but it is a limited, non-renewable nutrient resource, making its use vitally important. Nowadays, lower productivity in phosphorus availability is major concern. The decreasing ores and suboptimal levels of plant available phosphorus (P) can lead to lower yield. Its interaction with several other plant nutrients makes it very hard for plant availability. Several approaches have been tried and tested and many of them have been found effective, sustainable and cost efficient. However, the need for novel approaches for better phosphorus acquisition like physiological manipulation, better root structure and genetic alteration will help for resource conservation and is environmentally sustainable. But to diagnose environmental impact on excess use of phosphate fertilizers more improvement is required in order so that limited phosphorus stocks can be managed. Thus, there is a need for integrative approach to solve the lower P in soil system.

Introduction

The mere possibility of phosphorus (P) ores becoming scarcer in future has posed a danger to global agricultural systems (Cordell *et al.,* 2011). While, in terms of crop availability, phosphorus is a tricky element. But it will be difficult for policymakers in a country like India, where the government spends billions of rupees on fertiliser subsidies despite rising fertiliser production costs. One of the key variables limiting fertility and agricultural productivity is soil P. The plants need it for root germination, energy currency for meristem growth, nitrogen fixation, flowering, and maturation, and meristematic growth strengthens straw and reduces the likelihood of lodging. However, the regulation of metabolic pathways and for the control of important enzyme processes inorganic phosphorus

is also required. In plant growth, phosphorus is the second most often limiting macronutrient. It can cause stunted growth, low seed quality, and delayed maturity. The majority of the samples examined for available P in soil were found insufficient, and just a few were optimal, while total P was in a good amount, comparable to available P. India imports a large amount of phosphatic fertiliser from other countries, putting a strain on the Indian government. About 1-2 tonnes/ha are lost due to sheet erosion, pH imbalances cause fixation on either side of the pH scale, and leaching into streams causes eutrophication, disrupting natures delicate balance. Further, the runoff from

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agricultural lands is deposited in rivers and other bodies of water, making them non-source points of pollution that are difficult to remediate. In water critical limit of phosphorus is 0.03 mg L^{-1} dissolved phosphorus and over which eutrophication is likely to occur in 0.2 mg L^{-1} total phosphorus (Brady and Weil, 2014). The build-up of P in soil, with no long-term consequences, resulted in enhanced crop yield and quality, thus Indian farmers are using P fertilizers in excess amounts.

Due to low efficiency of phosphorus fertilisers, scientists had to think of alternate ways to manage soil phosphorus rather than adding more inputs. Soil P management has become an important aspect for optimal crop growth without any visible or invisible side effects due to vertical leaching of soil P, which is main reasons of decline and also is a source of groundwater contamination. In 2017-18, the actual NPK (Nitrogen, Phosphorus, and Potassium) consumption ratio was 6.10:2.46:1, as compared to the desired ratio of 4:2:1. Although this is a slight improvement above the consumption ratio of 7.23:2.9:1 in 2015-16, it is still a significant improvement (The Hindu 9th Oct 2019). In this heavily farmed area, 35% of the people tested surpassed the phosphate limit set by drinking water standards, according to a study of groundwater quality from wells in the Palar and Cheyyar River basins in Tamil Nadu, India (Rajmohan and Elango, 2005). So, to reduce the chemical usage of phosphorus in soil, various agronomic and chemical management strategies are necessary. However, the low phosphorus levels are due to soluble phosphate's high reactivity with other elements. In acidic soils, for example, phosphorus is combined with Al and Fe compounds (Norrish and Rosser, 1983) whereas calcium phosphate is the most prevalent inorganic phosphate (Lindsay *et al.,* 1989).

Factors for improving availability of phosphorus/PUE:-

1. Liming effect on soil P

Plants absorb phosphorus mostly as $H_2PO_4^{-1}$ and HPO_4^{-2} to a lesser extent. Soil pH determines the availability of these ions. Phosphate ions are absorbed by aluminium and iron cations at acidic pH. Higher organic matter and alkalinity were able to keep soluble P at a higher pH range, according to an aquaponics study. Plant available P remains poor in pH. Liming can increase soil phosphorus availability in a variety of ways, but it can also decrease availability by forming insoluble calcium complexes such as MCP, DCP, and apatite over time. Liming reduced the total organic phosphorus content of incubated surface samples of seven acid soils from eastern Canada by 3.6 percent in a laboratory experiment. Liming is suggested to minimise the toxicity of aluminium in the rhizosphere. Liming is also reported to enhance the intake of micronutrients like iron, boron, zinc, copper, and magnesium by balancing the pH.

2. Root Architecture

To live and finish its lifespan, phosphorus deprivation causes adaptive metabolic and structural modifications. Plants respond to low P levels in the soil by changing their root architecture, either by increasing root hairs or increasing root density. In some lowland rice genotypes, P deficiency increased the rate of organic acid exudation by 81 per cent (Hoffland *et al.,* 2006).

For solubilizing P, citric and oxalic acids are the most effective of the acids released (Hinsinger, 2001). Rhizosphere acidification reduces the pH of the bulk soil by 2-3 units. As a result of the acidification, various organic acids such as citrate and oxalate are secreted, causing the dissolution of various compounds and organic phosphorus through chelation and ligand exchange. Due to enhanced stimulation of root growth at the expense of shoot growth, an increase in root-to-shoot dry weight ratio is a common response to P deficit (Mollier and Pellerin, 1999). According to Roger and Benfey (2015) the presence of root hairs and the morphology of root tips aids in root penetration and anchoring inside the soil. Plant roots also release specialised metabolites such as phyto-siderophores in addition to organic acids. Siderophores are low-molecular-mass compounds that chelate iron in the rhizosphere while also releasing P from Fe-bound-P (Guan *et al.,* 2000).

3. P Solubilizing Microbes

The search for the efficacy and promise of P solubilizing microorganisms began in the 1960s and has continued since then. *Bacillius megaterium* and *Pseudomonas striata* are the most common bacteria engaged in P solubilization, while *Aspergillus awamori* and *Penicillium* have been observed in fungal species. It may be a realistic solution in terms of P management, but it is not particularly popular among farmers. The reason for this can be rationalised by the fact that low organic carbon content is a requirement for these bacteria in Indian subcontinent circumstances. Another reason is that this PSM only works in a very low temperature and humidity range. There are not a lot of convincing reviews on how effective they are. In their study, for the P-deficient calcareous Aridisol, Gunes *et al.* (2009) discovered that increased P availability resulted in significant P-fertilizer savings. Both microorganisms enhanced strawberry yield and mineral concentrations above what could be attained merely by fertilising with P.

4. Effect of tillage

Tillage has a variety of effects on soil parameters such as bulk density, erosion control, infiltration rate, water holding capacity, and soil compaction. So that conservation tillage, zero tillage, minimum tillage and no-tillage have a beneficial effect because these types of tillage practises disturb the soil minimally and thus loss is negligible as compared to deep tillage or conventional tillage practises. Tillage is also thought to have an impact on biochemical changes in the soil, which modify the liable fraction of soil nutrients. Gradual increase in soil MBC (microbial biomass carbon) and N were resulted in the minimum tillage residue retained (MT+R) treatment, while the lowest levels were obtained in the conventional tillage residue removed (control) treatment. Continuous no-tillage approaches can successfully enhance the amount of nutrients accessible in the soil. No-tillage methods can not only improve the amount of accessible P in the soil, but they can also efficiently maintain a constant soil P supply throughout the maize growing season (Xomphoutheb *et al.,* 2020). It is critical to establish adequate tillage and fertilisation methods in order to reduce fertiliser loss in agricultural production in order to maintain sustainable agricultural development and safeguard the environment. The availability of phosphorus is depending on the production system used (Carvalho *et al.,* 2014).

5. Effect of mulching

In 2009 and 2010, according to Vijay Kumar (2011), farmyard manure mulch had the highest soil OC (organic carbon) (6.65 and 6.85 g/kg), soil available N (239.00 and 240 kg/ha), soil available P (20.21 and 22.01 kg/ha) and soil available K (170.02 and 174.27 kg/ha). Mulching facilitates nutrient redistribution in the soil, reduces gaseous nutrient loss, and adds nutrients through decomposition of crop and mulch residues, all of which help to keep nutrients in the soil longer and boost plant uptake capacity (Amin *et al.,* 2014; Liu *et al.,* 2015; Rychel *et al.,* 2020; Wang *et al.,* 2020).

6. Agronomic practices

Good agronomic methods increase the build-up of nutrients in the soil and hence improve their bio-availability which could improve nutrient utilisation efficiency and nutrition uptake. Agronomic methods can reduce phosphorus fixation and increase phosphorus availability in soils (Horst *et al.,* 2011). Several agronomic strategies have been proven to increase the efficiency of P fertiliser use on agricultural fields (Simpson *et al.,* 2011 and McLaughlin *et al.,* 2011). However, there are numerous opportunities to reduce external P inputs by effectively manipulating soil crop and environment.

a. For Band Placement of Fertilizers

The way fertiliser is applied has an impact on the speciation of the P fertiliser reaction product (Khatiwada *et al.,* 2012). To maintain phosphorus available for plants, banding phosphorus fertilisers is a preferable agronomic method. When phosphatic fertilisers are broadcast or mixed with soil, they interact with more soil components and are swiftly transformed into insoluble complexes with calcareous soils calcium proportion (Malhi *et al.,* 2002). In-band placements of P fertilisers are more successful at reducing P-fixation and hence improving fertiliser efficiency in P-fixing soils. The amount of interaction between the soil and fertiliser is significantly reduced as a result of band placement, lowering P fixation. P fertiliser is kept in an accessible state for a longer period of time because to band placement, which improves P-uptake. When compared to the broadcast form of P administration, increased crop output and P accumulation in plant tissues have been documented in canola (Rehim *et al.,* 2012) and wheat (Karamanos, 2017). The distribution of P fertiliser in the soil at a site where P can contact active roots of the crop plant has been associated with increased fertiliser band placement efficiency. The banding enhances the likelihood that the root surface will be in close proximity to the fertiliser, which is more essential than increased P availability (Sleight *et al.,* 1983). Deep–banding methods, which apply fertilisers deep below the soil surface, are indicated for cereal crops grown on alkaline calcareous soils. Banding below the seed permits budding radicle and seminal roots to come into direct touch with the fertiliser, as per Gokmen *et al.* (1999). Thus, there are two management methods which are for promoting P nutrition in the agricultural system are banding P fertiliser in or near the seed-row and maintaining soil P levels by long-term fertiliser oversight (Rehim *et al.,* 2012; Grant *et al.,* 2001).

b. Increasing the root surface/soil contact area

This can be accomplished by altering the morphology of the roots. The roots having a longer specific root length (i.e., roots with a smaller diameter) can cover a larger area while maintaining the same level of root biomass. Increased hair root development is another method for accomplishing the same goal. P uptake efficiency in wheat is influenced by root fineness or branching (Jones *et al.,* 1989). As long as there is evidence of high genetic variability for this trait in wheat, this route appears promising. However, the current time-consuming and labour-intensive methodologies limit its use in breeding programmes that require the screening of large numbers of genotypes. Improving plant root systems ability to forage for this very immobile nutrient is one of the most important strategies for increasing P efficiency in agricultural systems (Richardson *et al.,* 2011). A variety of root morphological and architectural changes could be used to improve P absorption. Plants improve overall soil exploration through lengthening roots, branching roots, lengthening particular roots, and changing branching angles (Lynch and Brown, 2001; Gahoonia and Nielsen, 2004a; Lynch, 2007).

c. Increasing the effective root area

Root symbiosis with arbuscular mycorrhizal fungi (AMF) has been demonstrated to increase the effective root area, hence enhancing P absorption (Haymann and Mosse, 1971). P influx (P uptake per unit root length) is improved by AMF infection. On the other hand, a lack of consistency is seen in the information available about the genetic diversity present among wheat cultivars when it comes to vesicular-arbuscular mycorrhiza (VAM). Alternatively, wheat cultivars were thoroughly examined for the mycorrhizal association that only show minor changes among genotypes, which were not highly connected to increased P absorption, it was revealed during CIMMYT's (Manske *et al.,* 2000b). VAM is known to boost Cu and Zn uptake while decreasing Mn availability, in addition to P uptake.

d. Increasing nutrient availability

Nutrient availability and uptake, ranging from protons to complex chemical compounds can be affected from the root's exudates. To convert poorly available organic P, phosphatases are considered good which makes up 45-55 percent of a plants total P supply into inorganic forms that are more readily available to the plant (Randall, 1995). Root phosphatase secreted or bound at the basis surface differs according to genotype (McLachlan, 1980). An andisol study in wheat and triticale cultivars found a link between acid phosphatases and P absorption (Portilla Cruz *et al.,* 1998)

e. Crop species/variety

Plant breeding programmes can improve P use efficiency by identifying and selecting genotypes/species that are more effective in absorbing P from soils. Genotypes with efficient and wide root systems, as well as those with effective linkages with mycorrhizal fungi to access a larger soil volume are linked to this (Lynch, 2007).

f. Cover Crops and Conservation Tillage Practices

For minimizing tillage and keeping a minimum 30% crop residue on farm conservation tillage is recommended. The use of cover crops can also help to minimize P (Geohring *et al.,* 2011; Reid *et al.,* 2011). Conservation tillage is a process that involves integrating crop wastes into the soil (Gynor and Findley, 1995). This practice has been shown to reduce overall P losses and minimize particle bound P export (Ulen *et al.,* 2010). While it can improve nutrient efficiency, and cover crops can also reduce erosion and leaching. It produces rhizo-deposits that allow for the uptake of soil P (Nuruzzaman *et al.,* 2005). Some plant species, such as the Lupinus albus, can effectively solubilize soluble soil P (Braum and Helmke, 1995). This allows them to use soil as a cover crop or rotation (Njeru *et al.,* 2014).

g. Organic amendments

I tis known that the addition of organic manures in the soil can overcome the problem of soil P limitation. However, this method requires the proper quantity and quality of this practice (Kwabiah *et al.,* 2003). An organic residue can help to improve the soil's conditions by increasing the plant's available P. After breakdown, the organic manures can convert soil P into chemical form from native places (Smith *et al.,* 1998). The release of CO_2 occurs when soil's pH is lowered to a level that allows the uptake of H_2CO_3 (Mujeeb *et al.,* 2008). The organic acids released by the microbial decomposition process help in the breakdown of the soil's P.

Organic compounds that are generated during decomposition may boost the availability of P by covering or anionizing P adsorption sites or by releasing organic P into the soil (Nelson and Janke 2007). It is also important to note that organic compounds, which include phytin, are responsible for around 20% of total soil Phosphorus. Also, farmyard manure increases the microbial load on soils (Araujo *et al.,* 2009). To create a variety of organic acids and organic waste matter operation of soil microbe's breakdown was occurred (Liu *et al.,* 2017). Microbes help in the decomposition of organic debris, which helps in the release of nutrients slowly to the crop (Habai *et al.,* 2016). Increase in soil physical properties aid in P uptake by aiding root spread and enhancing mycorrhizal development (Cavigelli *et al.,* 2003; Medina and Azcon, 2010). Combination of inorganic fertilizers in conjunction with organic amendments resulted in increased crop yields and reduce liability on others inputs. Inorganic P fertilisers that are used in conjunction with FYM have been shown to improve their efficacy by lowering P fixation in the soil, boosting bioavailability, and extending the time they are available in the soil (Reddy *et al.,* 1996). Rock phosphate has a poor solubility in neutral and alkaline soils, but a higher solubility in acidic soils (Hongqing *et al.,* 2001). More solubilization was done when co-composting rock phosphate in combination with organic manures was applied (Akande *et al.,* 2005) (Tian and Kolawole, 2004). The release of organic acids during the decomposition of organic components can explain the increase in available P in rock phosphate (Kolawole and Tian, 2007).

h. Composting

Organic waste materials (composted) are recognized to reinforce manufacturing via means of improving soil physical, chemical, and biological properties as compared to raw organic waste materials (Ahmad *et al.,* 2006; Ogbonna *et al.,* 2014). During compost production, raw organic matter undergoes physical, chemical, and organic alterations, ensuing in large degrees of stabilised organic matter. As these stabilised organic components degrade, nitrogen and phosphorus are released into the soil (Sullivan *et al.,* 2003; Franklin *et al.,* 2015). This method is one of the efficient methods to boom bioavailable P and, as a result, enhance P availability from many organic materials. After composting, P conversion (Natural rate) into inorganic compounds (insoluble) is decreased. The organic component of the soil rises during the composting process, allowing for greater microbial activity and diversity. Humic material which are fresh drastically increase the addition of tens of thousands and thousands of native bacterial groups to the soil. The exothermic nature of composting contributes in the formation of various bacterial habitat.

All of these microbial communities degrade organic waste by feeding on it. During the breakdown process, organic acids are released. Some organic acids aid in the formation of a symbiotic interaction with root-invading fungus. Symbiotic partnerships with root colonisation fungi aid in increasing nutrient uptake from the soil. The composting process also aids in the convert nearby insoluble P sources so that they can converted into available form. In this process, insoluble P minerals are dissolved which react with CO_2 with the soil solution to form carbonic acid. The compost's physical, chemical, and biological activity all work together to provide long-term P nutrition to the growing plant (Kucey *et al.,* 1989).

i. Arbuscular Mycorrhizal Fungi

Root systems of most of the plants interact with symbiotic interactions that is widespread soil habitant in AMF. Over 400 million years, plants had a long relationship with AMF and this relationship resulted in a slew of positive outcomes. Multiple studies have shown that increased AMF colonisation of the host plant roots increases nutrient absorption (Smith and Smith 2011).

AMF plays a role in modifying P and increasing its In cereals plants like Rice, the more relevant pathway for absorption of P is AMF. Fine hyphae of AMF were extended when more P was absorbed by Plants and also surface area was also exposed to the soil. When total P uptake by the plant roots was increased it will gradually increase symbiosis benefits among the plants. Lower soil pH was resulted in AMF- assisted soil, which benefits the mineralization of phytate as a result, host plant transmission and P bioavailability for AMF absorption was increased (Wang *et al.,* 2013). Acid phosphatase enzyme activity is increased with AMF effect on plant P uptake (Feng *et al.,* 2003). In the vacuoles, AMF hyphae store polyphosphate enzymes. These enzymes have a strong selectivity for cleaving P bound to organic phosphates and converting them to an inorganic form. In the host plants, AMF arbuscules and inorganic P is transported. During Starvation AMF has a great role in P nutrition, when P is applied alone only 49 per cent absorption was done as compare to AMF, 78 per cent absorption was done (Thingstrup *et al.,* 2000). bioavailability in soils (Fitter *et al.,* 1991).

Conclusion

This paper highlights how to overcome P deficiencies and their management. It is seen that today agriculture system is more dependent on intensive agriculture farming, relying too much on cereals may also cause fewer improvements in phosphorus availability. In the future, farm outputs may be affected which also increase the cost of cultivation and decrease farm income. With the scarcity of P, food security and stability are going to be affected. Soil and plant with soil interactions need to be understood to understand more about P availability. Also, more research is needed in numerous components of agricultural systems, and better strategies need to be developed to meet out the issue of boosting plant P availability, while increasing the crop yield in a sustainable manner.

Conflict of interest

The authors declare that they have no conflict of interest.

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