Review Article

ADVANCES FOR IMPROVING PHOSPHORUS USE EFFICIENCY IN AGRICULTURE

Abstract:

An impending crisis is the continuous availability of phosphate fertilisers, which underlie global food production. The rock phosphate deposits on which the world depends are not only finite, but many are polluted and many are located in geopolitically unstable locations, implying that significant changes will be required to maintain food supply for an increasing global population. There is no single solution, but a combination of phosphorus management measures is required not just to extend the life of the remaining non-renewable rock phosphate sources, but also to result in a more efficient, sustainable phosphorus cycle. Improving the effectiveness of fertiliser applications to agricultural land, as well as a better understanding of phosphorus cycling in soil-plant systems and the interplay between soil physics, chemistry and biology in conjunction with plant characteristics are among the solutions. The finite nature of rock phosphate supply and development of other sources of phosphorus fertilisers is unavoidable. There are clear prospects and it is now critical to prioritise a concerted effort to increase phosphorus usage efficiency.

Introduction:

Nutrient utilisation efficiency (NUE) is a significant element in agricultural production system evaluation. Fertiliser management, as well as soil and plant water management, can have a significant impact. The goal of nutrient utilisation is to improve ' overall performance of cropping systems by giving economically optimal nourishment to the crop while minimising nutrient losses from the field. NUE addresses certain aspects of that performance but not all. As a result, system optimisation objectives must incorporate both overall productivity and NUE.

Because of its numerous functional and structural roles in plants and soils, phosphorus (P) is an essential nutrient for plant growth and development. Plants absorb phosphorus as phosphate and anion from soil solution. It is the least movable component. Because of its sluggish diffusion and high fixation in soils, P is difficult to make available to plants. To achieve maximum output, a sufficient amount of soluble phosphatic fertiliser is applied. However, phosphatic fertilisers that are applied in soluble form quickly become unavailable to plants. The phosphorus requirement for optimal growth is in the range of 0.3 to 0.5%.

When water soluble P fertilisers are applied to the soil, P rapidly reacts with different soil components and becomes unavailable through precipitation, with dissolved irons, aluminium, manganese (in acid soil), or calcium (in alkaline soil) to form phosphate minerals by conversion into less soluble inorganic P fraction through fixation and retention. Desorption and dissolving reactions make the leftover portions available for future crop. Phosphorus becomes more difficult to release into soil solutions over time and as a result, the efficacy of P fertilisers in soil remains low.

Recent approaches for improving phosphorus use efficiency in soil - plant system :

1. Doses and placement of phosphorus

Phosphorus placement can be broken into two general application methods: broadcast and band. Application of fertilizer to the soil surface, with or without subsequent incorporation by broadcasting. It is the simplest application method and is best suited for high-speed operations and heavy application rates. When ploughed or disked in, broadcasting produces the most uniform P distribution within the root zone and provides more root contact with P. It also maximizes contact between the soil and fertilizer so the opportunity for fixation is higher. Band applications concentrate the fertilizer in narrow zones or bands that are kept intact to provide a concentrated source of nutrients. Banding is advantageous where soil test levels are low, where early season stress from cool or wet conditions is likely to limit root growth and nutrient uptake and for soils that have a high tendency to fix P in unavailable forms. Phosphorus may be banded prior to, during, or after planting.

Rehim*et al*. (2010) discovered that band application of P increased the P content of the straw and grain, resulting in higher P uptake of the straw and grain. The advantage of band placement of P at higher P levels could be attributed to the fact that developing roots in band placement were in close contact with P-enriched soil near to fertiliser granules rather than broadcasted P and lower P levels. Nonetheless, owing of the little soil contact, there was little probability of P adsorption in band placement over broadcast. (Singh *et al.*, 2000; Delong *et al*., 2001; Imtiaz *et al*., 2003 and Alam *et al.,* 2003).

Table 1 : Recent approaches for improving phosphorus use efficiency in soil - plant system :

Sr. No.	**Approaches**	**Treatments**	**Crops**	**PUE (%)**	**References**
1	Placement and Dose	Band placement	Wheat	Without FYM-9.37	Rehim*et al.* (2011)
				With FYM-13.62	
		150 kg/ha P_2O_5	Wheat	31.177	Ghafoor (2016)
2	Soil amendments	NPKSCa	Wheat – maize cropping system	85.00	Qaswar *et. al* (2020)
3	Fertigation	Fertigation	Maize	24.7	Iqbal *et al.* (2013)
		RD of P through fertigation at 1st irrigation	Maize	17.00	Javid *et al.* (2015)
4	Plant Strategies				
a	Root foraging strategies	At low P	Soybean genotype	-	Vandamme *et al.* (2012)
b	Soil phosphorus mining strategies	Citric acid treatment		-	Tsado*et al.* (2014)
c	Transgenic approach	*ex::phyA-3* gene	Tobacco	-	George *et al.* (2004)
		osavp1dox gene	Rice	-	Gaxiola *et al.* (2011)
5	Nano-fertilizers	ZnO Nano particles (1000µg) in pure culture		-	Tarafdar *et al.* (2012)
		Nano ZnO (10 ppm)	Clusterbean	-	Raliya and Tarafdar (2013)
		Nano ZP @ 100 %	Peanut	ARE of P - 32.90	Hagab *et al.* (2018)
6	Phosphate solubilizing micro-organism	100% RDP with PSF	Wheat	Total P uptake - 25.7 kg/ha	Ram *et al.* (2014)
		20 kg P_2O_5 kg/ha +	Mungbean	ARE of P	Yadav

		PSB + VAM		- 12.49	(2017)
7	Integrated nutrient management	FYM @ 10 t/ha under finger millet-groundnut rotation	Finger millet based cropping system	ARE of P - 18.85	Shilpa and Vasanthi (2021)
8	Controlled release fertilizers	Polymer coated DAP at 50% rate of recommended dose	Wheat	ARE of P - 55.76	Sobia *et al.* (2017)
		liquid paraffin coated products used in wheat field	Wheat	P release- 97.3 mg P /kg soil	Sarkar *et al.* (2018)
9	Management practices	Interculture + Gliricidia cover + maize stover @ 20 kg P_2O_5/ha	Maize-chickpea cropping system	7.21	Chaudhary *et al.* (2018)

Elevated PUE due to band placement of P compared to broad casting and top dressing might be due to the greater fixation of broadcast P than the applied in bands because of narrow soil to fertilizer ratio in the later situation, since P sorption maxima depends on the ratio of soil to applied P (Sultani *et al.*, 2004; Alam *et al.*, 2005). Similarly, higher PUE at lower P levels was most likely the result of intensive root competition and thus efficient utilisation of applied P. Plants used a lesser proportion of fertiliser P at greater P application rates, resulting in a low PUE. Ghafoor (2016) indicated that higher P concentration in grain of wheat was increased significantly with increasing P application rate to the soil. The results were in agreement with the results finding by Rehim*et al*. (2010) and Sushanta *et al*., 2014, they found that the total P uptake by wheat increased with increasing P fertilizer application.

2. Application of soil amendments

Changes in soil acidity through fertilization can strongly influence the soil nutrient availability, plant growth and functionality of ecosystem. The acidification of soil reflects the relative distributions of acidic cations (H^+ and Al^{3+}) and base (Ca^{2+}, Mg^{2+}, K^+, and Na^+) cations with the capacity to neutralize the acidic cations that mostly depend on exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. As the amount of H^+ ion increases, the concentration of base cations decreases during ecosystem development. Due to soil acidification, some negative effects may appear in soil such as depletion of base nutrients, high solubility of Al, Fe and Mn, which may cause toxicity in plant.

Qaswar *et al*. (2020) compared to fertiliser treatments without lime application and fertiliser with lime application considerably boosted P absorption and P usage efficiency (PUE) during different fertilisation years. P uptake increased by 154%, 461%, 472%, 717%, 1168% and 1236% under NP, NPK, NPKS, NPCa, NPKCa and NPKSCa fertilisation treatments, respectively. PUE in the above treatments was 20.7 kg/kg, 66.2 kg/kg, 64.4 kg/kg, 105.1 kg/kg, 187.6 kg/kg, and 185.0 kg/kg on average during the years. Because quicklime application significantly increased PUE and crop yield by increasing soil pH and base cations (Ca^{2+} and Mg^{2+}) and reducing the exchangeable Al^{3+}. Highest increase of crop yield and PUE were under the NPKCa and NPKSCa treatment, due to retention of SOC by straw and mitigation of acidification through liming. While, liming decreased soil available P in NPKCa and NPKSCa, compared to NPK and NPKS treatments, respectively.

3. Fertigation

P-fertigation seems to be an innovative technique where nutrients in the form of solution are applied through irrigation water to reach the crop roots rapidly, which is also an effective means of controlling the time and placement of fertilizers and improving fertilizer use efficiency by reducing nutrient losses from leaching and/or fixation in the soil to less available forms. Overall, inefficient P use with surface application of dry P fertilizer results in excessive P fixation in soil and less consumption by crops and increases production costs. Thus much applied P is fixed by soil minerals, particularly on the crops where the soil is derived from volcanic ashes. Fertigation P is the practice of applying P fertilizers with the irrigation water by injecting fertilizer into the flowing water of an irrigation system.

Papadopoulos (1994) reported that in calcareous soil having high pH, fertigation was superior to conventional soil P application. Alam *et al*. (1998), Latif and Iqbal (2001), Latif *et al*. (2002), Alam *et al.* (2003), and Hussein (2009) also demonstrated the fertigation as a more efficient method of nutrient management than broadcast method. Phosphorus applied by fertigation resulted in improving the P efficiencies as compared to its soil mixing at sowing. Latif *et al*. (2001) discovered that when a lesser dose of nitrogen was combined with a full dose of P and delivered through fertigation, the P absorption was equal to that of a full dose of N and the same dose of P. It demonstrates that crop benefitted the most from balanced P supply by fertigation. During three cropping seasons, P uptake by fertilisation was substantially higher than P uptake by broadcast technique (Iqbal *et al*. (2013). Over the three crop seasons, fertigated applied P led to increases in mean P-uptake, agronomic efficiency, and P utilisation efficiency of 17, 65 and 90%, respectively, over broadcast technique. Fertigation had a P use efficiency of 24.70%, whereas broadcast application had a P use efficiency of 13.03%. These results demonstrated that fertigated P application outperformed the broadcast technique.

Javid *et al.* (2015) discovered that phosphorus uptake by grain, stalk and total was greatest when the recommended dose of P was administered *via* fertigation rather than broadcast. According to Memon *et al.* (2011), low broadcast P recovery indicates relatively high P fixation and conversion of applied phosphates to a less accessible form due to the alkaline calcareous character of soil. Similarly, Latif *et al.* (1997) and Hussein (2009) reported that maize plant receiving P in solution form at first irrigation contained significantly higher P content as compared to P applied by broadcast at sowing. Higher PUE at lower P level might be the result of intense root competition and thereby an efficient exploitation of applied P fertilizer The potential advantages of fertigation include improved fertilizer use efficiency, flexibility in timing of fertilizer use in relation to crops demand, increased crop yield and improved quality of the produce.

Plant strategies

A) Root foraging strategies

Phosphorus use efficiency can be obtained either through (i) increased P uptake efficiency, defined as the ability to maintain levels of P uptake at suboptimal P availability relative to P uptake at optimal P availability, or (ii) increased P utilization efficiency, defined as the ability to utilize P taken up for the production of biomass. Among both, breeding for increased P uptake efficiency is considered most promising (Lynch, 2007). Increased P uptake efficiency is related to a range of root characteristics, *i.e.*, (i) root growth and architecture (root to shoot ratio, distribution among root types, root angles), (ii) root morphology (root diameter, root hair development, aerenchyma), (iii) rhizosphere processes (acidification, phosphatase activity, exudation of organic acids) and (iv) symbiosis with mycorrhizal fungi (reviewed by Gahoonia and Nielsen, 2004; Lambers *et al*. (2006); Lynch, 2007; Ramaekers *et al*., 2010). These root characteristics can be the result of either features that are expressed irrespective of environmental conditions or genotype-specific environmental response.

Vandamme *et al.* (2013) found that biomass accumulation and total P uptake at low P was highest for Namsoy4m and Nyala and lowest for Pan-872 genotype of soybean. P utilization efficiency was lower at high P for all genotypes, but remained unaffected by genotype. Differences in P uptake efficiency among genotypes were largely related to differences in root hair development and to a lower extent to colonization by mycorrhizae. The situation under field conditions is however likely to be more complex with other root traits such as root angles and branching possibly affecting P uptake.

B) Soil phosphorus mining strategies :

Organic acids have a very important chemical significance especially for the mobilization of various phosphates in soil. In addition, Jones *et al.* (2003) and Palomo *et al*. (2006) reported that secretion of organic acids (such as citric, tartaric, oxalic acids *etc*) from plant root was the major mechanism for enhancing P availability in soils and hence improving crop yields. The supply of P to plants is also strongly influenced in the rhizosphere by the presence of organic acids (Hue *et al.*, 1994). This introduces the concept that it may be possible to mimic a plant's release of organic acids by artificially incorporating acids in to the soil which would increase P availability in soils with low P status. According to tsado*et al*. (2014), organic acids significantly increase P mobilization and the effectiveness of organic acids to release P occurred in the order of citric acids > tartaric acids > oxalic acids.

C) Transgenic approach:

Phytases, enzymes that hydrolyse derivatives of inositol penta and hexakis phosphates are of particular interest because phytate constitutes up to 50% of the total organic P in soil (Turner *et al.,* 2002). Paradoxically, many plants have limited capacity to obtain P directly from phytate when grown under controlled conditions. This is because the availability of phytate in soil is low (due to sorption and precipitation reactions (Hayes *et al*., 2000; Richardson *et al.,* 2000; Richardson *et al.,* 2001a; Celi *et al*., 2001 and Idriss *et al*., 2002) and because the capacity of plants to exude phytase to the rhizosphere is limited. In low P-sorbing growth media (agar or sand), the ability of plants to use P from phytate is improved when they are inoculated with soil micro-organisms which possess phytase activity, or when purified phytase is added to the medium.

Tobacco grown by George *et al.* (2005) in soil supplemented with phytate, transgenic plants that expressed ex::phyA accumulated more P in shoots than did control plants. The shoot biomass in the phyA-expressing line (ex::phyA-3) was increased by 38% when compared with the control plants grown in the soil collected from fertilized plots. P accumulation by transgenic plants expressing ex::phyA was also significantly improved by 34% compared with control plants in this soil.

Gaxiola *et al*. (2011) suggested that the AVP1DOX rice lines (OsAVP1DOX) exhibited sustained shoot growth under Pi-deficient (10 µM) conditions while the controls grew poorly. Moreover, these lines developed more robust root systems than controls in both Pi-sufficient and P-deficient conditions. Therefore, AVP1 overexpression in both monocots and dicots results in enhanced root systems and increased soil acidification capacity under low Pi conditions. Importantly, it also enhances the extraction capacity of P by crops under both P-deficient and P-sufficient conditions. The generation of AVP1-transgenic corn with enhanced Pi uptake capacity could help to alleviate the severe environmental impacts currently associated with this crop (Diaz and Rosenberg, 2008; Donner and Kucharik, 2008).

4. Nano-fertilizers

Tarafdar *et al.,* (2012) demonstrated the effect of ZnO nanoparticles on phosphatases released by both the fungi showed enhancement in acid phosphatase and alkaline phosphatase by *Aspergillus terreus* CZR1. The phosphatases secretion by *Aspergillus flavus* CZR2 was enhanced by 50.8% (acid phosphatase) and 80.4% (alkaline phosphatase). Zn application as either normal oxide or nano-scale oxide was invariably associated with higher acid and alkaline phosphatases. The increase was more in case of ZnO nanoparticles application and that too in *Aspergillus terreus* CZR1, although the production of acid phosphatase by both the fungi was higher than the alkaline counterpart. ZnO nanoparticles may enhance polysaccharide secretion of fungi *Aspergillus terreus* CZR1 and *Aspergillus flavus* CZR2 by 8–9 folds. The extracellular polysaccharides secreted in the media by industrial microorganisms is to known improve the quality of the product.

As Zn is the structural component of phosphorous (P)-mobilizing phosphatase and phytase enzymes, it can be hypothesized that application of nano ZnO may help in more secretion of P-mobilizing enzymes, which is involved in native P mobilization for plant nutrition from unavailable organic sources (Tarafdar and Claassen, 2003). Raliya and Tarafdar (2013) indicated increased activity of P nutrient-mobilizing enzymes *viz*., phytase, acid and alkaline phosphatase in the rhizosphere due to sprayed of nano-ZnO at 10 mg/L concentration on 2-week-old clusterbean plants than ordinary size and control.

Hagab *et al.* (2018) showed that the apparent recovery efficiency of P at a rate of 100% was 18.40, 32.90 and 23.70% for SP, NZP and ZP, respectively. When only a rate of 50% of the recommended rate from nano source was used, the recovery efficiency was higher than applying 100% of the ordinary source in both the first and the second seasons. This indicates that NZP can be used as a potential and economic alternative source to other sources. Therefore, using NZP would help in reducing the quantity of the applied fertilizers and consequently the farmers' profitability.

5. Phosphate solubilizing micro-organism

Ram *et al*. (2015) showed that the P content in grain increased with PSF at 0% P level only, which was similar to that in 50% P with no PSF. Similarly, total P uptake in grains plus straw was significantly higher in PSF over no PSF at 0% P level only. On average, PSF increased the P uptake by 11.6% in 0% P treatment. The increase in P uptake with PSF was possibly due to the increase in available P in the soil through solubilisation of inorganic P fractions in the soil. The increase in P uptake in several crops with the inoculation of PSB was also reported by many researchers (Rodríguez and Fraga, 1999 and Gulati *et al.*, 2007).

Yadav *et al.*, (2017) observed that raising the level of phosphorus from 0 to 20 kg/ha registered the highest agronomic efficiency and apparent recovery of phosphorus after that, it showed significant decline up to 60 kg/ha. The more supply of phosphorus might regulate starch/sucrose ratio in source leaves and reproductive organs. The beneficial effect of phosphorus on fruiting of plants and better translocation of desired metabolites to the yield contributing parts of the plant might attributed to more grain yield. These findings collaborate the results of Tanwar *et al.* (2003), Rathore *et al.* (2010) and Kumawat *et al.* (2013) in urdbean and Singh and Sekhon (2007) in mungbean. Dual inoculation of seed and soil with PSB + VAM recorded significantly highest agronomic and apparent recovery than rest of the treatments. This occurs due to increased solubilization and mineralization of organic phosphorus and availability of nitrogen and phosphorus (Kumar *et al.*, 2014).

6. Integrated nutrient management practices

With respect to grain yield and total amount of phosphorus applied, Shilpa and Vasanthi (2021) revealed that partial factor productivity of phosphorus (PFPP) was much higher ranging from 24.28 kg/kg under finger millet mono-cropping to 110.50 kg/kg under finger millet- groundnut rotation. Agronomic efficiency and apparent recovery of phosphorus were also considerably higher under finger millet- groundnut rotation. In general, phosphorus use efficiency was quite higher with lower application rate of phosphorus and decreased with incremental rate of nutrient application. Plots receiving organics were having lower content of available phosphorus compared to integrated application of manures and fertilizers. This might be ascribed to the higher response and better utilization by finger millet to applied phosphorus in later plots. Further application beyond this point was nonbeneficial and non-economical as plants utilized a smaller proportion of applied phosphorus, leaving the remaining amount fixed in the soil (Chandrakala, 2014). Higher phosphorus use efficiency in case of organically maintained treatments may be due to higher biomass production as compared to nutrient input supplied and improvement of soil physico-chemical and biological properties with the use of organic FYM and rotational cropping. Similar findings were reported by Tarik and Mani (2017) and Zhu *et al.* (2012).

7. Use of controlled release fertilizers

Sobia *et al*. (2017) showed that agronomic and recovery efficiency of P was increased with decreasing the rates of polymer coated DAP fertilizer. The maximum increase in P agronomic efficiency was recorded in polymer coated DAP than uncoated DAP application. Similarly, Zahrani, 2000 and Hopkins *et al.*, 2008 observed the maximum recovery efficiency was in polymer coated DAP over uncoated DAP application. Due to the slower and gradual release from coated fertilizers can be helpful in term of reduced frequency of application and also minimize the negative effects associated with over dosage.

Sarkar *et al.* (2018) observed that polyvinyl alcohol coated CRRPFs released higher amount of P (116.5 mg/kg) over the liquid paraffin coated products (97.3 mg P /kg soil). Release of P from uncoated commercial DAP was 326.9 mg P/kg soil. Gordon and Tindall (2006) revealed that controlled release P-fertilizers may be dependent on soil type as well as the moisture movement through porous materials and their nutrient contents release gradually and coincide with the nutrient requirement of a plant.

8. Effect of management practices

Chaudhary *et al.* (2018) revealed that maximum PUE value of 7.21 kg/kg P_2O_5 applied was recorded under MCP_4 (Inter culture + Gliricidia cover + maize stover). Similar results were reported by Kushwah*et al.* (2016) in soybean-wheat system under *Vertisols* of Central India. Minimum value was recorded under MCP_1 (control) being 4.0 kg/kg P_2O_5 applied. A comparison of PUE across various MCPs for different P doses revealed that P_{20} recorded higher PUE of 5.55 kg/kg P_2O_5 applied, which was at par with PUE under P_{40} doses (5.30 kg/kg P_2O_5) applied. The moisture conservation practices integrated with proper root augmenting P nutrition helped in growing chickpea crop under rainfed maize–chickpea system.

Nadeem *et al.* (2018) recorded maximum nitrogen and phosphorus uptake by wheat (107.4 and 25.58 kg/ha) were significantly greater with the manual hoeing and with the application of 150 kg N + 100 kg P_2O_5/ha (W_4 x F_2). This was followed by post-emergence application of Isoproturon + carfentrazone ethyl with 150 kg N + 100 kg P_2O_5/ha (W_3 x F_2). Minimum nitrogen and phosphorus uptake by wheat was obtained in the weedy check with no fertilizer application (W_1 x F_0). Maximum fertilizer use efficiency was obtained with post-emergence application of isoproturon + carfentrazone ethyl was statistically similar to manual hoeing and minimum was obtained with a weedy check. The increased dose of fertilizer has increased nutrient uptake by wheat as well as by weeds. However, increased nutrient losses due to greater uptakes by weeds at higher fertilizer rates can be successfully reduced through suitable weed control practices. Among the various fertilizer doses and weed control practices, higher fertilizer rate and manual weeds control rendered more NPK use efficiency and grain yield, followed by higher dose of fertilizer. Therefore, efficient use of fertilizer can be achieved through effective weeds control practices. Thus, in order to achieve higher grain yield and higher fertilizer use efficiency, weeds should be controlled along with the use of greater fertilizer levels.

Conclusion

From the forgoing discussion some agronomic practices like application of phosphorus through band placement with appropriate rate, application of soil amendment (lime in acid soil), fertigation, INM, nano fertilizers and CRF with some management practices *viz*; moisture conservation and weed management helped in improving PUE. Besides these, some plant strategies *viz*; root foraging, P mining and transgenic approaches enhanced P availability. Among all the approaches use of nano sources of fertilizers and CRF were found with highest PUE owing to the minimized the pollution hazard as well as slower and gradual release of P from coated fertilizers helped in term of reduced frequency of application and also minimized the negative effects associated with over dosage.

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