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## Phosphorus management strategies to enhance P-use efficiency and sustainable crop production

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### Abstract

With increase in food grain production in India from 50.8 million tonnes (Mt) in 1950-51 to 295.67 Mt in 2019-2020, the production and consumption of phosphorus (P) fertilizer has also increased from 9.8 thousand tonnes in 1950-51 to 4790 thousand tonnes in 2019-2020 and from 6.9 thousand tonnes in 1950-51 to 7464 thousand tonnes in 2019-2020, respectively (FAI 2020). Phosphorus is the second important primary nutrient element after nitrogen. Low P use efficiency is the significant challenge for agricultural production on P-deficient soil as well as in acidic and calcareous soils (Shenoy *et al.* 2005). Acquisition of soil and fertilizer P by crops depends on soil and plant properties. Soil processes determining P availability to plants are P solubility/sorption, P transport, root/soil contact and mineralization/ immobilization (Horst *et al.* 2001). Agronomic strategies for enhancing P use efficiency includes selection of fertilizer, soil test based P application, methods of P fertilizer application, fertigation, residual P utilization by different crops, utilization of insoluble P sources by addition of organic matter and phosphate solubilizing microorganisms (PSM), integrated nutrient management (Subba Rao 2010). Improved P use efficiency has been observed by Mengel (1997) in acidic soil by applying P at the time of sowing and liming. The two main strategies which help plants to improve P use efficiency are (i) root-foraging strategies that improve P acquisition; and (ii) P-mining strategies to enhance the desorption, solubilization or mineralization of P from sparingly soluble sources in soil using root exudates (Richardson *et al.* 2011).

**Keywords:** Phosphorus, management, efficiency, sustainable

### Introduction

Phosphorus play an important role in crop plants, animal and micro-organisms as a component of nucleic acid, phospholipids that compose cellular membranes, ATP and ADP molecules (Taiz and Zeiger, 1998) <sup>[18]</sup>. It influences plant growth by helping plants effectively utilize sugar and starch and in the process of photosynthesis, cell division and nucleus formation. Phosphate compounds act as storehouse of energy produced during the process of photosynthesis and carbohydrate metabolism. Deficiency of P is an significant challenge for agricultural productivity on acidic and calcareous soils in many regions of the world. P-fertilizer use in agriculture on P-deficient soils that are moderate to highly P-sorbing, is often relatively inefficient (Weaver and Wong, 2011) <sup>[21]</sup> due high P-fixation in soil. Soil processes determining P availability to plants are P solubility/sorption, P transport, root/soil contact and mineralization/ immobilization (Horst *et al.*, 2001) <sup>[9]</sup>. Agronomic strategies for enhancing P use efficiency includes selection of fertilizer, soil test based P application, methods of P fertilizer application, fertigation, residual P utilization by different crops, utilization of insoluble P sources by addition of organic matter and phosphate solubilizing microorganisms (PSM), integrated nutrient management (Subba Rao, 2010) <sup>[16]</sup>. High quality rock phosphate reserves are finite and there is an on-going debate about the longevity of global P resources (Van Kauwenbergh, 2010) <sup>[19]</sup>. For moderate to highly P-sorbing soils, this implies systems in which P-fertilizer input amounts are much closer to equaling the amounts of P exported in products (Syers *et al.*, 2008) <sup>[17]</sup>. However, farming systems that have lower P-fertilizer requirements because they export less P in products are also possible (Richardson *et al.*, 2011) <sup>[13]</sup>.

### Phosphorus use efficiency

Phosphorus is the second most limiting nutrient after N in most of the soils and is unavailable to plants under most soil conditions (Vassilev *et al.*, 1996) [20]. Continued long-term application of P fertilizers and organic wastes and manures can lead to accumulation of P in surface horizons due to the low crop use efficiency (<25%) in the year of application.

- Apparent P recovery =  $(TU_p - TU_c \times 100) / AF_p$
- Agronomic use efficiency (kg grain kg applied P<sup>-1</sup>) =  $(GY_F - GY_C) / AF_p$
- Production efficiency (kg grain/kg P absorbed) =  $(GY_F - GY_C) / (TU_p - TU_c)$

### Where

$TU_p$  = Total P uptake from fertilized plot (kg/ha)  
 $TU_c$  = Total P uptake from unfertilized control plot (kg/ha)  
 $AF_p$  = Amount of applied fertilizer P (kg/ha)  
 $GY_F$  = Grain yield in fertilizer plot (kg/ha)  
 $GY_C$  = Grain yield in unfertilized control plot (kg/ha)

### Phosphorus fertilizer consumption and production

Food grain production of India continuously increased from 50.8 million tonnes (Mt) in 1950-51 to 295.67 Mt in 2019-2020 (Department of agriculture and cooperation). The production and consumption of phosphorus (P) fertilizer of India has also increased from 9.8 thousand tonnes in 1950-51 to 4790 thousand tonnes in 2019-20 and from 6.9 thousand tonnes in 1950-51 to 7464 thousand tonnes in 2019-20, respectively (Fertilization association of India, 2020).

### Fate of applied P fertilizer in soil

Phosphate is fixed largely through precipitation with iron and aluminium in solution (strong acidic soil), and by reaction with iron and aluminum hydrous oxides. Phosphorus is fixed by hydrous oxides of Al and Fe by anion exchange on silicate clays (moderately acidic soil). In slightly acidic soils, P is fixed by hydrous oxides of Al and Fe and by silicate clays, as insoluble CaSO<sub>4</sub>. In alkaline soils the soluble P from fertilizers react initially with Ca form Di calcium Phosphate which later becomes octa-calcium phosphate. Both of these

compounds have limited water solubility, but they do provide P to plants. With time, these compounds revert to more insoluble form of phosphate, such as tricalcium phosphate and hydroxyl apatite. Even this insoluble compound is slowly available to plants. Thus the fixation of P does not result in the completely irreversible loss of available phosphate from the soil but continuous to provide p to crop on limited scale over an extended period of time. The fixation of phosphate in relation to different soil pH is presented in (Figure 1).

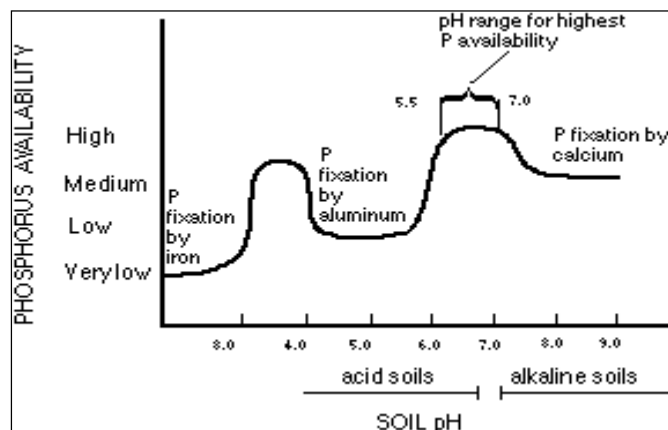


Fig 1: Effect of pH on P-fixation

### Strategies for enhancing P use efficiency

- Choice of fertilizer
- Soil test based P application
- Phosphorus placement
- Fertigation
- Residual P utilization
- Utilization of insoluble P sources
- Mobilization of P through earthworm
- Integrated nutrient management
- Application of lime and proper application time of P in acid soil

### Choice of fertilizer

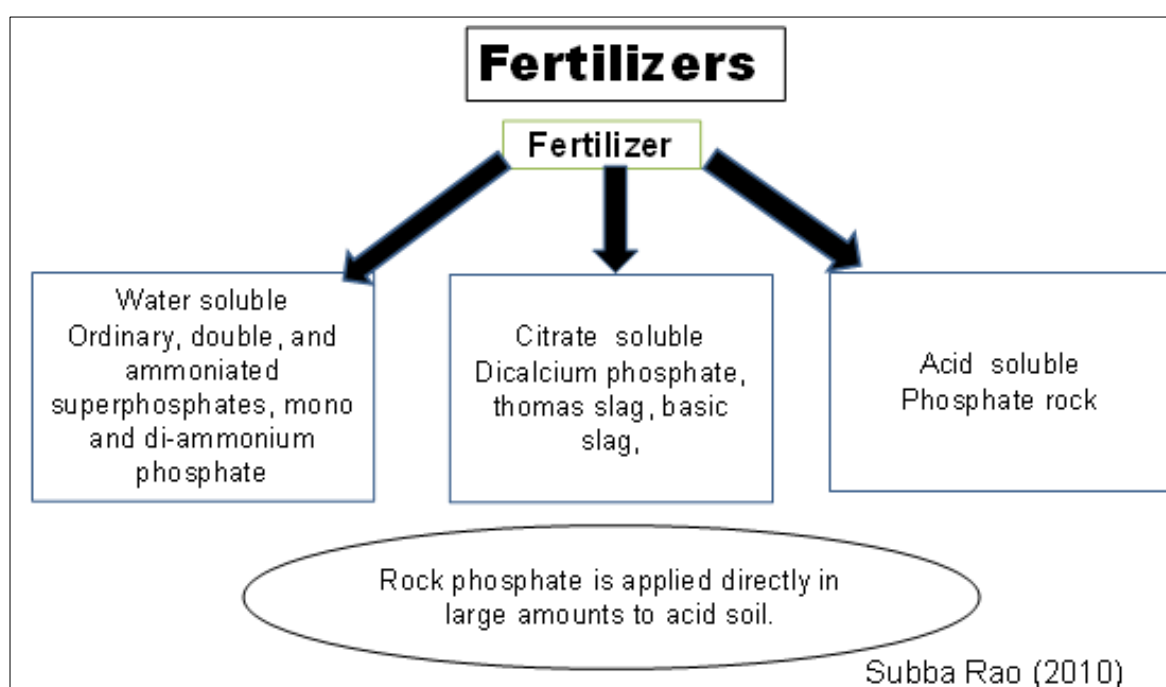


Fig 2: Classification of P-fertilizer on the basis of solubility

According to A. Subba Rao P fertilizers are divided into three groups on the basis of solubility; the water soluble group, citrate soluble and acid soluble (Fig. 2). The rock phosphate and bone meal are applied directly in large amounts to acid soil, where the sparingly soluble phosphates are converted into a form usable by plants.

#### A. Polymer-coated water-soluble phosphorus fertilizers

Recently, some fertilizer companies have developed thin coating of water soluble phosphorus (WSP) fertilizers (DAP, MAP, TSP) with water-insoluble polymers, with or without S (e.g., trade name "DAP-Star"), as a slow-release P fertilizer. Another type is coated with water-soluble polymers (e.g., trade name "Avail") to reduce the rate of WSP conversion to water insoluble P by soil fixation. Gordon and Tindall (2006) [6] claimed that Avail is a polymer with a very high surface charge density (about 1800 cmol kg<sup>-1</sup> of cation exchange capacity) that can inhibit P precipitation by acting as a platform for sequestration of P-fixing cations, such as Ca and Mg in high pH soils and Fe and Al in low pH soils.

For instance, it is known that WSP is adsorbed or precipitated on the solid surfaces of Fe and Al oxide minerals in acid soils and CaCO<sub>3</sub> in alkaline soils. What mechanism causes these Fe, Al, and Ca cations to dissolve from their minerals and diffuse to the dissolved polymer-coated WSP granule sites, be adsorbed by the polymer via ionic exchange, and thereby protect the WSP from precipitation? Furthermore, shouldn't the soluble cations associated with the WSP fertilizers (Ca ions from SSP and TSP, and NH<sub>4</sub> ions from MAP and DAP) be first adsorbed by the polymer and thereby reduce the polymer's capacity to sequester soil Fe, Al, and Ca ions? Research is needed to address these questions in order to understand the merit of using WSP fertilizers coated with water-soluble or water-insoluble polymers. If indeed P release meets the crops' needs, and at the same time minimizes P fixation, the coated WSP fertilizers may be effective for crop production provided the cost/benefit is feasible compared to the uncoated WSP fertilizers.

#### B. Rhizosphere-controlled fertilizer (RCF)

The "rhizosphere-controlled fertilizer" (RCF fertilizer) are specific fertilizers having nutrient release patterns that are dependent on plant activity in the rhizosphere. This fertilizer is based on the introduction of an organo-mineral matrix composed of metal [Mg (Ca is also possible), Zn (Fe and other metals are also possible)]-humic phosphates. The presence of this matrix modifies the nutrient release pattern of the fertilizer. In this way there are two main nutrient fractions: (i) a water-soluble fraction or "starter" fraction and (ii) a "rhizosphere-controlled" fraction insoluble in water but soluble by the action of the rhizospheric acids released by plants and microorganisms. The "starter" fraction has the function of assuring adequate onset of the plant cycle and the "rhizosphere-controlled" fraction has the function of covering plant nutritional needs for the rest of the plant cycle, while minimizing nutrient losses. This fraction would be formed by those nutrients that are released by the action of rhizospheric organic acids and may consist of an organic or inorganic matrix formed by water-insoluble compounds that can be solubilised by the action of rhizospheric organic acids.

A study conducted by Erro *et al.* (2011) [2], it was reported that RCF was most efficient P source for plants in acid soil (Table 1). Phosphorus extraction by wheat grown on acid soil was higher from RCF treated soil as compared to soils treated with SSP and dicalcium phosphate (DCP). The higher availability of P in RCF treated soil may be attributed to the presence of water-soluble fraction or "starter" fraction along with the humic moiety in the MHP which prevents the formation of highly insoluble phosphates in the presence of Fe and Al in acid soil. Even though the acidic environment should facilitate solubilization of P from DCP but plants are less efficient in mobilizing P from DCP in acid soil due to presence of higher concentration of Al and Fe.

**Table 1:** Effect of variable doses of P supplied through RCF and other P-fertilizers on P extraction by wheat crop grown on acid soil

Treatment	Doses (mg of P kg <sup>-1</sup> of soil)				
	5	15	30	50	100
<b>Plant P extraction (mg)</b>					
SSP	0.02 ab	0.04 b	0.23 b	0.99 a	2.83b
RCF	0.07 a	0.10 a	0.38 a	1.32 a	4.42 a
DCP	0.02 b	0.06 ab	0.11 c	0.39 b	1.79 c

Erro *et al.* 2011 [2]

#### Soil test based P application

Soil testing is a must for optimizing the use of P and for obtaining economic yield of crop on agricultural soils. Fertilizers/manure P rates on soils with medium phosphorus value need to be sustained for higher crop productivity. In low available P and high-responsive soils, adequate P greatly increases crop yields. However, on soils with very high P, a small maintenance dose of P may be sufficient.

#### Phosphorus placement

Phosphorus application is divided into two general categories: broadcast or band placement. Broadcast is application of fertilizer to the surface of soil, with or without subsequent incorporation. Broadcast is the simplest application method and is best suited for high-speed operations and heavy application rates. When plowed or disked in, broadcasting produces the most uniform P distribution within the root zone and provides more root contact with P. However, it also maximizes contact between the soil and fertilizer so the opportunity for fixation is greater. Band applications that concentrate the fertilizer in narrow zone or band that are kept intact to provide a concentrated source of nutrients.

#### Fertigation

Fertigation is the application of fertilizers, soil amendments, or other water-soluble products through an irrigation system. According to Iqbal *et al.* (2003) [10] fertigated SSP enhanced the grain yield (12.52%) of wheat significantly ( $p < 0.05$ ) while fertigated DAP increased it non-significantly over broadcast method. The yield potential was lower (4,882 kg ha<sup>-1</sup>) in fertigated DAP than that in fertigated SSP (5,249 kg ha<sup>-1</sup>, Table 2). This indicated that fertigation with DAP is less effective than fertigation with SSP. Application of DAP at the lower rate (33 kg P ha<sup>-1</sup>) through fertigation resulted in almost the same wheat yield as obtained by the higher dose (44 kg P ha<sup>-1</sup>) applied by broadcast method (Table 2).

**Table 2:** Effect of application methods on grain yield of wheat and phosphorus uptake in grain under field conditions

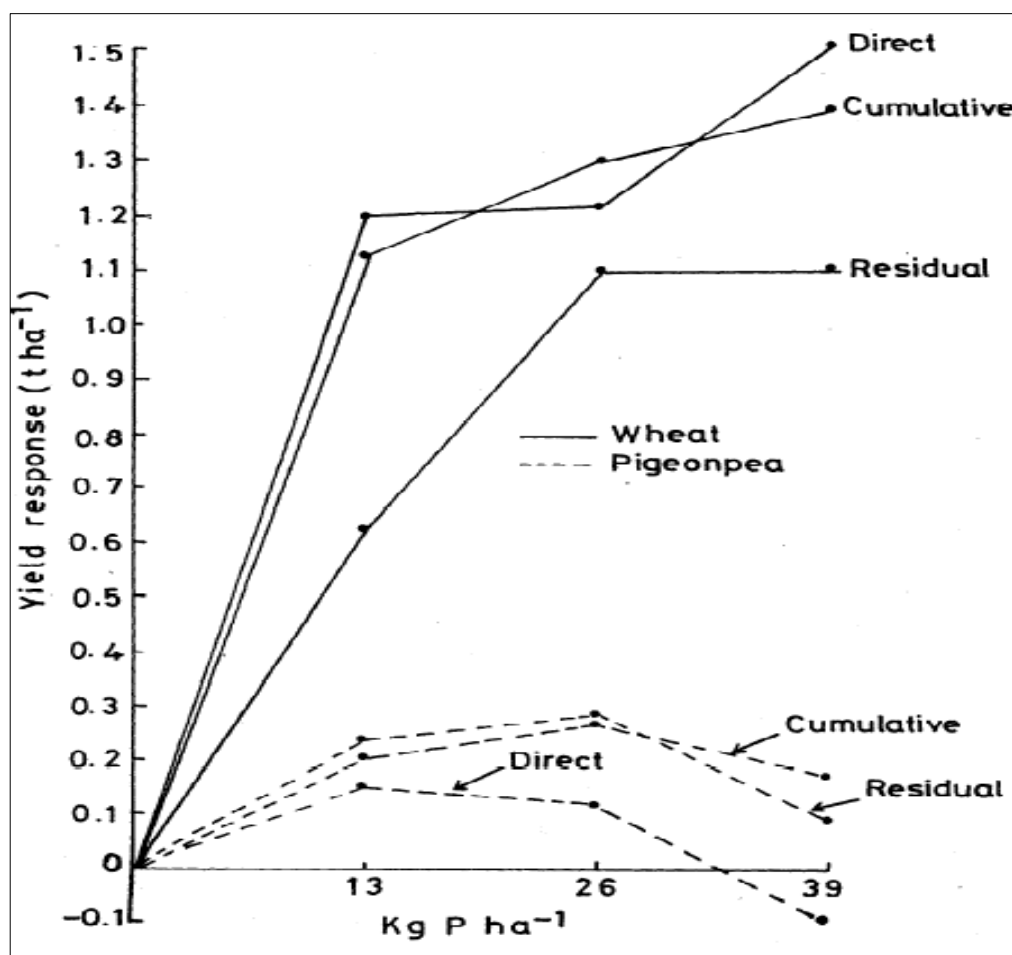
Fertilizer application				Grain yield	P uptake	PUE	AE
Source	P rate (kg /ha)	Method	Time	kg/ha	kg/ha	%	kg/kg
Control	-	-		3966	13.88		
DAP	44	Fertigation	1 <sup>st</sup> irrigation	4882	19.78	13.41	20.82
DAP	44	Broadcast	Sowing	4516	17.05	7.20	12.50
DAP	33	Fertigation	1 <sup>st</sup> irrigation	4443	17.38	10.60	14.45
SSP	44	Fertigation	1 <sup>st</sup> irrigation	5249	19.70	13.23	29.15
SSP	44	Broadcast	Sowing	4665	19.00	11.64	15.88
SSP	33	Fertigation	1 <sup>st</sup> irrigation	4854	18.99	15.48	26.91

Source: Iqbal *et al.* 2003 <sup>[10]</sup>

### Residual P utilization

The residual effect is generally lower than the effect of fresh applied nutrient. According to Bahl *et al.* (1998) <sup>[1]</sup> in pigeon pea, application of 13 kg P ha<sup>-1</sup>, averaged over the three phases of application, resulted in a significant increase in yield over control in only the second year of experimentation. However, in wheat, a significant increase in the grain yield, with the application of P up to 26 kg P ha<sup>-1</sup>, was observed in all three years. The response to applied P, averaged over three years, indicated much lower response in terms of grain yield of pigeon pea compared to that of wheat despite a low level of

Olsen extractable P in the surface soil (Figure 3). The grain yield of pigeon pea was significantly higher (8–15%) in the residual P treatment over the direct P application. The residual and cumulative P applications were not significantly different. However, in case of wheat, direct application of P resulted in significantly higher grain yields than the residual treatment, the increase being 12, 8 and 9% during the three years, in that order. P application to both crops did increase the grain yield of wheat compared to direct application to wheat only, but this was non-significant.



**Fig 3:** Grain yield response of direct, residual and cumulative applied P to pigeon pea and wheat (mean of 3 years) Source: Bahl *et al.* 1998 <sup>[1]</sup>

### Utilization of insoluble P sources

Most of the rock phosphates are reasonably suitable for direct use in acid soils, but have not given satisfactory results in neutral to alkaline soils. However, if the characteristics of rock phosphate and soils were not favorable for direct application, then it would be necessary to increase the solubility of rock phosphate by technological processes and/or biological means. Partially acidulating the rock phosphate

with mineral or organic acid or treating the rock phosphate with acidifying agents or organic amendments or its composting through biological means are some of the efforts aiming to enhance its effectiveness in neutral and alkaline soils.

### Addition of organic matter

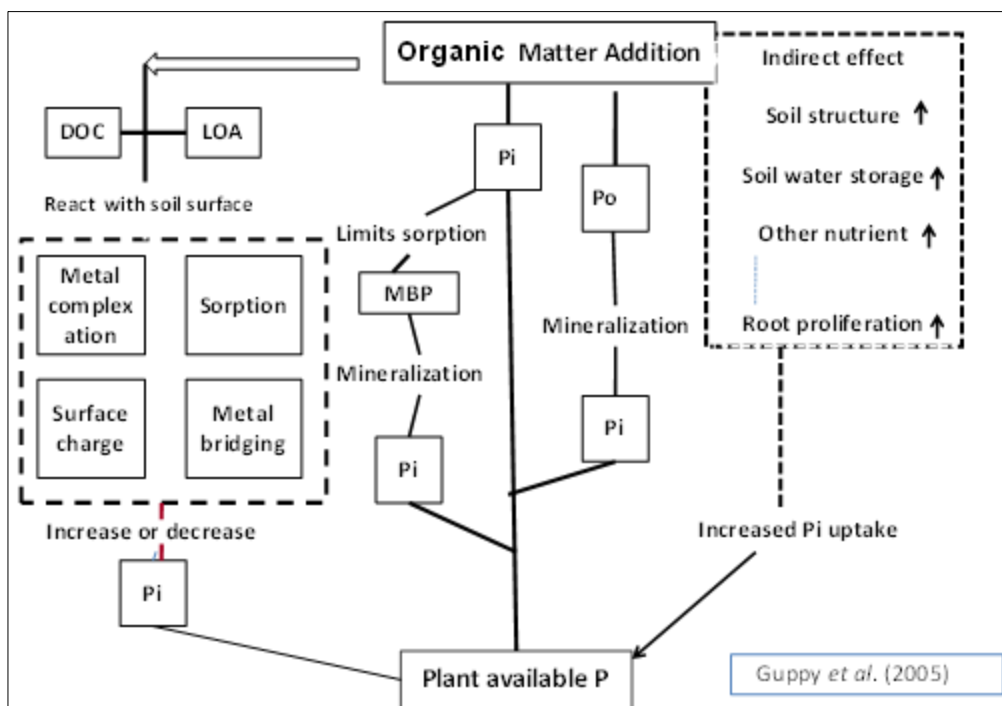


Fig 4: Mechanism of solubilization of inorganic P by adding organic matter

### Mobilization of P through earthworm

Earth worm enhances nutrient availability through casting mainly in tropical soils. The positive effects of earthworms on the availability of N and P to plants is due to increased microbial population and hence enzyme activity in the casts. Extractable P and S also showed significant increases in casts during incubation. In red soil casts, Bray's P (an estimate of available P in acid soils) increased 2-fold compared to non-ingested soil. In black soil casts the Olsen's P (an estimate of available P in neutral and calcareous soils) increased by more than 3-fold phosphate and a 2- to 12-fold increase in alkaline phosphatase.

**Integrated nutrient management:** According to (Reddy *et al.*, 2000) [12] mean soybean and wheat yields increased significantly with the application of cattle manure and fertilizer P (Table 3). It is evident from the data that the application of manure alone at the rate of 4, 8 and 16 t/ha increased the soybean seed yield by 42%, 57% and 75%, respectively, and wheat grain yield by 67%, 116% and 143%, respectively over control (no manure and no fertilizer P). When fertilizer P was also applied along with manure, the corresponding yield increases were 79%, 90% and 93%, respectively, in soybean and 159%, 181% and 197%, respectively, in wheat (Table 3) and so indicated the importance of integrated use of organic manure and chemical fertilizers.

Table 3: Effect of manure and fertilizer P application on crop yields and P uptake in soybean+ wheat rotation (mean of six years)

Manure application rate (t ha <sup>-1</sup> y <sup>-1</sup> )	Crop yields (t ha <sup>-1</sup> )		Uptake P (kg P ha <sup>-1</sup> )	
	Soybean	Wheat	Soybean	Wheat
<b>Without fertilizer P</b>				
0	1.13	1.52	7.67	2.34
4	1.60	2.54	12.68	5.73
8	1.77	3.28	14.45	7.40
16	1.98	3.70	17.29	8.75
<b>With fertilizer P (22 kg ha<sup>-1</sup>)</b>				
0	1.86	3.34	14.39	9.03
4	2.03	3.94	19.57	13.15
8	2.15	4.27	22.30	15.01
16	2.18	4.51	24.98	17.22
LSD P<0.05	0.11	0.28	1.65	1.47

Reddy *et al.* 2000 [12]

### Application of lime and proper application time of P in acid soil

#### A. Fertilizer application time

Influence of the contact time between soil and phosphate fertilizer (superphosphate) on its P availability for *Lolium perenne* grown in pots. From the ten soils tested only the results of the two extreme soils, an acid brown earth (7% clay, DLP= 9 mg P/kg soil, in KCl solution, pH 4.6) and a subsoil from a rendzina (67% CaCO<sub>3</sub>, DL-P = 0.8 mgP/kg soil, pH

7.6). According to these characteristics the first soil should favor phosphate adsorption and the latter the formation of less soluble Ca phosphates. Both soils were very low in available phosphate. In the acid soil the contact time had a highly significant impact on the phosphate uptake of the grass. Phosphate fertilizer, given 6 months before seeding, yielded a significantly lower recovery than phosphate fertilizer applied just before seeding. Also a 3 months contact time still had a significantly negative effect on the efficiency of the P

fertilizer. This pattern found in the first cut of the grass was also evident in the second cut. In the calcareous soil the fertilizer/soil contact time had no influence on the P uptake of the grass. Obviously there was no major formation of unavailable Ca phosphates during a period of 6 months otherwise the rates of phosphate uptake by the grass should have declined with an increase in the soil/fertilizer contact time (Mengel, 1997) <sup>[11]</sup>.

### B. By liming

Phosphate adsorption is a particular problem in highly weathered soils of the tropics (Oxisols and Ultisols) because of their high phosphate adsorption potential. For phosphate melioration they require high P fertilizer rates in the range of 170 kg P/ha (Haynes, 1984) <sup>[8]</sup>. Most of these soils are acid and require liming which does not improve phosphate availability in all cases. Liming may induce polymerization of Al cation species which because of their high positive charge are strong phosphate adsorbers (Haynes, 1984) <sup>[8]</sup>. According to Hauter (1983) <sup>[7]</sup> the decrease of phosphate availability due to liming of Oxisols is associated with their very low pH (3.7–4.4) while at a soil pH of 5.5 liming had a beneficial effect on phosphate availability. Sims and Ellis (1983) <sup>[15]</sup> reported that liming an Ultisol increased the available soil P and enhanced P uptake by oats considerably. In order to save fertilizer phosphate on these strongly phosphate fixing soils band placement of fertilizers is recommended.

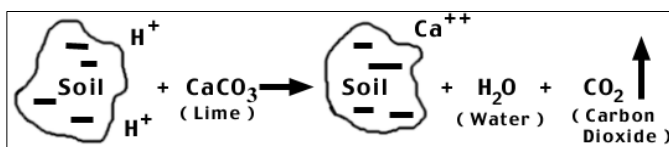


Fig 5: Reaction of lime in soil system

### Conclusions

Thin coated MAP was found to be superior in enhancing P-use efficiency over uncoated MAP. RCF was more efficient P source than SSP or dicalcium phosphate (DCP) in relation to P extraction by wheat grown on acid soil. Band placement of water soluble phosphatic fertilizers proved to be better than its broadcast application. Pigeonpea could utilize the residual P more efficiently, indicating that fresh application to this crop can be omitted. Earthworms could enhance P availability through casting.

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