

Phosphorus in relation to dominant cropping sequences in India: chemistry, fertility relations and management options

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Soils vary widely in their capacities to supply phosphorus (P) to crops because only a small fraction of the total P in soil is available to crops. Thus, the crop growth and yield are likely to suffer adversely unless soil is endowed with adequate native supply of plant-available P, or else the soil receives readily available (inorganic) P fertilizers. In order to rationalize fertilizer P application to support sustained high productivity on one hand and address the environmental and economic concerns on the other, an in-depth understanding of native P supplies and P dynamics in soil is inevitable. In this context, the present article takes stock of the available information on the occurrence of P in soils, chemistry of P in soil, P quantity, intensity, and buffer capacity attributes of different soils vis-à-vis the P uptake modelling, P dynamics in soil, P management in important cropping systems for enhancing its use efficiency, soil testing for plant-available P to prescribe fertilizer P application and losses of P through erosion and runoff to the water bodies leading to eutrophication.

Keywords: Cropping sequences, phosphorus dynamics, phosphorus in soils.

PHOSPHORUS (P) is essential to all forms of life and important for its contribution towards aiding the native soil fertility and sustaining it, especially under intensive agriculture. The economic challenges associated with increasing P fertilizer prices are driving the increased interest in improving P use efficiency¹. Moreover, transfer of soil P from cultivated land through erosion or runoff is a major cause of P-induced eutrophication in surface waters². This underlines the significance of P management taking care of native supplies and crop demands under a given cropping system or growing environment. In order to develop judicious P management options, it is essential to critically analyse the scientific knowledge

pertaining to different aspects governing the availability of native and applied P to the crops³.

Phosphorus in Indian soils

Phosphorus occurs in soil predominantly in the inorganic form, although organic forms of P may also contribute substantially (20–80%) to the total P content. In Indian soils, inorganic P generally contributes 54–84% of total P, whereas the share of organic P varies from 16% to 46% in different states⁴. Total P content varies from 120 to 2166 mg kg⁻¹ in majority of soils, although extremes of 44 mg kg⁻¹ to more than 3500 mg kg⁻¹ of soil have also been documented⁴. In most cases, total P content of soil is poorly correlated with plant available P, and thus not used as a measure of P fertility of soil.

Data on available P content of surface (0–15 cm) soil generated by soil testing laboratories has been compiled from time-to-time (Table 1)^{5–7}, that provide a measure of P fertility of Indian soils. In these compilations, soils of more than 90% of the districts represented low to medium P fertility categories indicating the necessity for P fertilization to produce optimum crop yields. Although, it may not be rational to assess the changes in P fertility status over time, these data clearly indicate that P fertility of most of the Indian soils continues to be extremely poor. Also, wide inter-regional variations exist in P fertility of soils, which are often masked in summarized country-level reports.

Table 1. P fertility status of Indian soils

Reference	Districts in fertility categories (%)			
	Districts studied	Low	Medium	High
6	226	47	49	4
7	363	46	52	2
5	500	51	40	9

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Chemistry of phosphorus in soil

Soil P exists in four different pools on the basis of its accessibility and extractability such as: soil solution P; surface-adsorbed P; strongly-bonded or absorbed P; and very strongly-bonded or inaccessible or mineral or precipitated P⁸. In the soil solution, P is immediately available for uptake by plant roots. The second pool represents readily extractable P held on the surface of soil components. This pool is considered to be in equilibrium with P in the soil solution, and can be transferred readily to the soil solution as the concentration of P in the latter is lowered due to P uptake by plant roots⁹. Researchers in India^{10,11} also recognize the existence of different pools of P in the soil and their accessibility to crops.

Kinetics of phosphorus sorption in soil

Phosphorus retention by soils is an important parameter for understanding soil fertility problems, as well as for determining the environmental fate of P¹²⁻¹⁴. A better understanding of the energetics of P sorption, based on kinetic studies, may help elucidate mechanisms of P adsorption-desorption in soils. In general, the Freundlich adsorption isotherm provides a better fit of the equilibrium phosphate sorption data in soils than does the Langmuir adsorption isotherm, especially so, at relatively higher concentrations of the phosphate. The Tempkin equation is based on a model in which the affinity term decreases linearly with the amount of adsorption^{13,15} and is termed thermodynamically¹⁶ superior over the other two.

Thermodynamics of phosphorus adsorption in soil

Following Sanyal *et al.*^{16,17}, the phosphate sorption process may be regarded as a process of partition of P between the bulk soil solution phase and surface phase. Such partition process is characterized by a distribution coefficient (K_0). By using the appropriate extrapolation technique¹⁷, it is possible to refer to the resulting standard differential Gibbs energy change (ΔG_0) values, accompanying the adsorption process to the limit of the infinitely dilute solution of the adsorbate (e.g. phosphate) corresponding to the minimum surface coverage at equilibrium. This would minimize the electrostatic interactions of sorbed P with charged surfaces of soil, or that between the sorbed P species themselves.

The negative magnitude of the ΔG_0 values would indicate the spontaneity of the given sorption process in the soils studied, while exhibiting significant correlations with the sorption parameters of different adsorption isotherms used to describe P-fixation by soils and soil components. In such an event, the stability of P sorption reaction products in soils, relative to P in soil solution, seems to contribute towards the P-fixing characteristics

of these soils¹⁷. Such information may profitably be incorporated into crop management practices when planning for an appropriate P source, rate, and timing of application for a soil, given its P sorption-desorption behaviour¹⁸⁻²⁰. Thus, for a soil with high P sorption capacity and strong P-binding energy, coupled with a high P sorption rate and poor P desorption characteristics, one may settle for a less soluble P source that releases P in soil solution in smaller concentrations, spread over a longer period of time. This is expected to slow down the P fixation reactions in the given soil, and maintain fertilizer P in plant-available form for a longer period¹⁷.

Phosphorus buffering capacity

The phosphate buffering capacity (PBC) of soil characterizes the dynamic relation between labile solid phase (quantity) and solution phase phosphate (intensity) from which plants receive their supply. Various indices used to express this parameter are: (i) the slope at a standard equilibrium concentration of $0.2 \mu\text{g ml}^{-1}$, (ii) the slope at a standard equilibrium concentration of $0.3 \mu\text{g ml}^{-1}$, (iii) the maximum slope of the isotherm as solution concentration tends to zero and (iv) the ratio between the change in quantity factor and intensity factor, designated as differential buffering capacity²¹. A closer linear relationship exists between P-buffering capacity and ability of soil to sorb phosphate. The PBC of the sandy soils is less than that of the fine-textured soils. The PBC of acidic and neutral soils is a function of the amount and extent of crystallinity of hydrated oxides of Fe and Al. In calcareous soils, the amount of exchangeable calcium and CaCO_3 determines the PBC^{21,22}.

Ligand exchange of phosphate

The ligand exchange is distinct from the simple anion exchange in that the phosphate, for example, in acid soil readily gets immobilized and removed from the soil solution, following a generous application of soluble phosphatic fertilizer, even in the presence of a strong (say 1 M) solution of NaCl. This tends to suggest that phosphate and chloride anions compete for different types of adsorption sites. The former is chemisorbed in soil, while the latter undergoes electrostatic (physical) retention¹⁶.

At a $\text{pH} > \text{ZPC}$ (zero point of charge, $\text{pH} 8.5$), the undissociated phosphoric acid molecule plays a key role in supplying the proton from one of its dissociable (OH) groups to protonate the OH^- ligand of Fe^{III} in goethite, thereby converting it to a neutral (H_2O) ligand which is then replaced by the negatively charged H_2PO_4^- ion, causing ligand exchange and phosphate fixation¹⁶. On the other hand, at pH equal to or less than the ZPC, the net negative charge of the soil colloid would increase as a result of ligand exchange, involving, say, phosphate. This

will lead to very high P fixation capacity of the soil, e.g. volcanic ash soils of the East Indies^{12,16}.

Hysteresis

Studies showed that desorption of P is always less than the amount of phosphate sorbed at a given equilibrium P concentration. This effect is known as hysteresis¹⁶ in P sorption–desorption behaviour. This implies that the sorbed P undergoes further interactions which impart to it a greater degree of affinity for the surface and causes difficulty in plant access to residual P build-up in a cropping cycle. In fact, desorption generally requires much more energy to disrupt the retentive forces which are primarily covalent in nature for inner-sphere complexes formed between the soil colloid and the added phosphate. This leads to irreversibility of the adsorption–desorption processes involved, with the degree of such irreversibility depending on the nature of the soil colloids concerned (e.g. aluminosilicate clay minerals, hydrous oxide of Fe, Al, etc. in clay-size dimensions), and also the ions concerned.

Modelling phosphorus dynamics in soil

In order to make effective use of the exhaustive data generated on different aspects of P in agriculture, i.e. its chemical interaction with soil and biological interactions with microorganisms, its use efficiency in relation to cropping systems and management, measurement of its availability, etc. development and use of models assume great significance. The model described here (Figure 1) is conceptually similar to a model given by Jones *et al.*²³. The rectangles in the diagram indicate state variables which define the state at a particular time and the arrow with valve indicates flow of material from one state variable to another at a certain rate. This is a dynamic deterministic model which contains the time variable t explicitly and needs as many number of ordinary differential rate equations as the number of state variables predicting the rate of change of the state variables.

In this model, total P in soil is distributed in organic and inorganic pools. Organic P is divided into the fresh

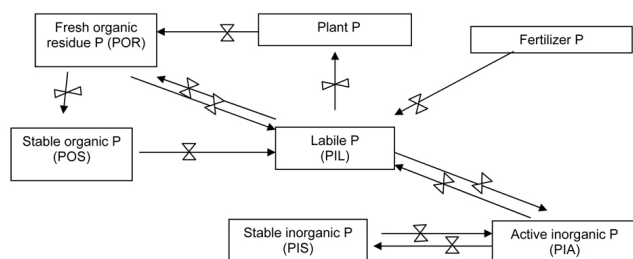


Figure 1. Phosphorus dynamics in soil–plant system.

residue P pool (POR) consisting of P in undecomposed residues obtained from plant growth and microbes (OR) and the stable organic P pool (OS). Inorganic P is divided into labile P (PIL), and non-labile P which is further divided into active P (PIA) and stable P (PIS). The common pool between inorganic and organic P is the labile P (PIL), which is also connected to plant P and fertilizer P. This is the simplest approach. The complexity of the model will increase if more number of pools of organic matter are considered.

Phosphorus uptake model

To predict the diffusive and the mass flow movement²⁴, the labile P has to be partitioned into solution P, adsorbed P and PBC. Earlier, the buffering capacity was considered as linear for simplicity, but in fact, it is curvilinear and is modelled by following the Freundlich or the Langmuir isotherm. Such buffering capacity is not constant due to slow reaction of P with soil solids and also due to pH changes and the presence of other specific anions such as organic acids, silicate, bicarbonate, etc. Recently De and Datta^{25,26} modelled the effect of pH and time by modifying the Freundlich equation. The model accurately predicted²⁷ P uptake in a soil with high P (52 μM) in soil solution. In soil with low P (7.8 μM in the soil solution), however, the predicted P uptake accounted for only 30–35% of the measured uptake. To correct this model, release of P in the rhizosphere from non-labile source due to P depletion by root and organic acid secretion by root has been accounted²⁸. This model has to be optimized and validated under different cropping systems and soil types.

Soil testing for phosphorus

The inorganic P occurring in the soil solution is immediately available to plants and is exclusively orthophosphate. Other inorganic forms are largely unavailable although changes in pH can render them available. A few organic forms of P are potentially available, and these are the main source of orthophosphate other than direct fertilization with soluble phosphate. Bray²⁹ proposed that an acceptable agronomic soil P test should have the following characteristics.

- The soil test should extract all or a proportionate amount of the plant-available P from soils with differing chemical and mineralogical properties.
- The soil test should be accurate and rapid.
- The P extracted by the soil test should be well-correlated with plant P concentration, plant growth, and the response of the plant to added P in fertilizers or manures.
- The soil test should accurately detect differences in soil P concentrations caused by earlier fertilization or manuring.

Several methods for determining available soil P have been developed to provide a basis for fertilizer recommendations^{30–44}.

Interpretation of fertilizer response data vis-à-vis soil testing values

The soil fertility ratings (low, medium and high) for P proposed during the 1950s on the basis of magnitude of crop response to nutrient input remained almost unchanged although the entire spectrum of agriculture has transformed since then, particularly with respect to P removal and response pattern of exhaustive crop varieties. When crop responses to P application are similar for both 'medium' and 'low' P soils as indicated by multi-locational on-farm experiments (Table 2)⁴⁴, a fertilizer prescription formulated for such a 'medium' fertility soil would be essentially sub-optimal. Hence, these ratings need to be revised in the light of current crop responses to applied P on different soils, and used for interpretation of soil test data.

Plant–microbe interactions in phosphorus acquisition

The root-induced rhizosphere processes not only determine mobilization and acquisition of soil nutrients as well as microbial dynamics, but also control nutrient use efficiency by crops, and thus profoundly influence crop production and sustainability⁴⁵. Therefore, manipulating root growth and rhizosphere processes through microbial strategies provides an effective approach to improve nutrient use efficiency and crop productivity simultaneously^{46–51}. (Please see the article by Elangovan *et al.* in this special section, p. 1315).

Phosphorus in crop production systems

Phosphorus removal under dominant cropping systems

On-farm studies conducted under All India Coordinated Research Project on Integrated Farming Systems (AICRP-IFS, earlier AICRP-CS) have clearly shown that P uptake was maximum in crops when all the macro-

nutrients and micronutrients were applied in optimum amounts (Figure 2). Application of P along with N increased P uptake by 21% to 25% in rice–wheat, 10% to 13% in rice–rice, 30% to 34% in maize–wheat, 12% to 40% in pearl millet–wheat, and 23% to 26% in cotton–wheat system in *kharif* and *rabi* crops respectively, over N application alone. The added increase due to K over NP was 9% to 33% under different cropping systems. Skipping micronutrients resulted in 11% to 34% lower P uptake under these cropping systems. Comparatively, lower P uptake under farmers' fertilizer management practice (FFP) may be ascribed to continuous neglect of K, S and micronutrients⁵². On Typic Ustochrept soils of Modipuram, combined use of 120 kg N and 26 kg P ha⁻¹ in rice and wheat not only produced high yields compared with addition of N alone, but the agronomic efficiency and apparent recovery of fertilizer N and P in rice and wheat also increased significantly^{53–57}.

Phosphorus management strategies under different cropping systems

Fertilizer P management in rice–wheat system (RWS) is of particular significance because of distinct growing conditions of rice and wheat that lead to alternative anaerobic and aerobic soil environments. In rice, submergence creates reducing conditions which leads to reduction of ferric phosphate to ferrous phosphate, resulting in a greater availability of P in the soil^{12,53}. Organic acids formed under submerged conditions also solubilize phosphates. Hence, in RWS, application of fertilizer P to wheat produces a better residual effect on the following rice crop. Nevertheless, while summarizing the results of AICRP-IFS, no definite conclusion could be drawn as to whether P should be applied to wheat or rice or to both crops. On loamy sand soils of Ludhiana, flooded rice crop did not respond to applied P, but the subsequent wheat did. Fairly recent studies on similar soils have, however, shown that the best approach is to apply P to both crops⁵⁴. In sandy loam soils of Modipuram, skipping of fertilizer P application to either crop resulted in significant yield loss over P application to both the crops⁵⁵. In view of varying reports, skipping of P application to rice in RWS would depend on soil type, P supplying capacity, relative distribution of different forms of P in the soil, submergence regime and productivity level.

Site-specific nutrient management (SSNM) studies conducted under RWS for attaining 10 t ha⁻¹ hybrid rice and 6 t ha⁻¹ wheat grain yield indicated that a soil sufficient in available P for moderate yield (6 t ha⁻¹ rice and 5 t ha⁻¹ wheat) immediately falls under P responsive category with increasing production targets. Accordingly, P requirements increased for both rice and wheat crops. Optimum P fertilizer rates (P-opt) ranges between 14.6 and 27.7 kg ha⁻¹ for rice, and from 19.4 to 32.7 kg ha⁻¹

Table 2. Average response of wheat to 60 kg P₂O₅ ha⁻¹ in on-farm trials on the soils of low, medium and high fertility status

Fertility rating	Districts	Trials	Response (kg ha ⁻¹)
Low	21	2140	680
Medium	17	2446	669
High	1	147	486

Source: Ref. 44.

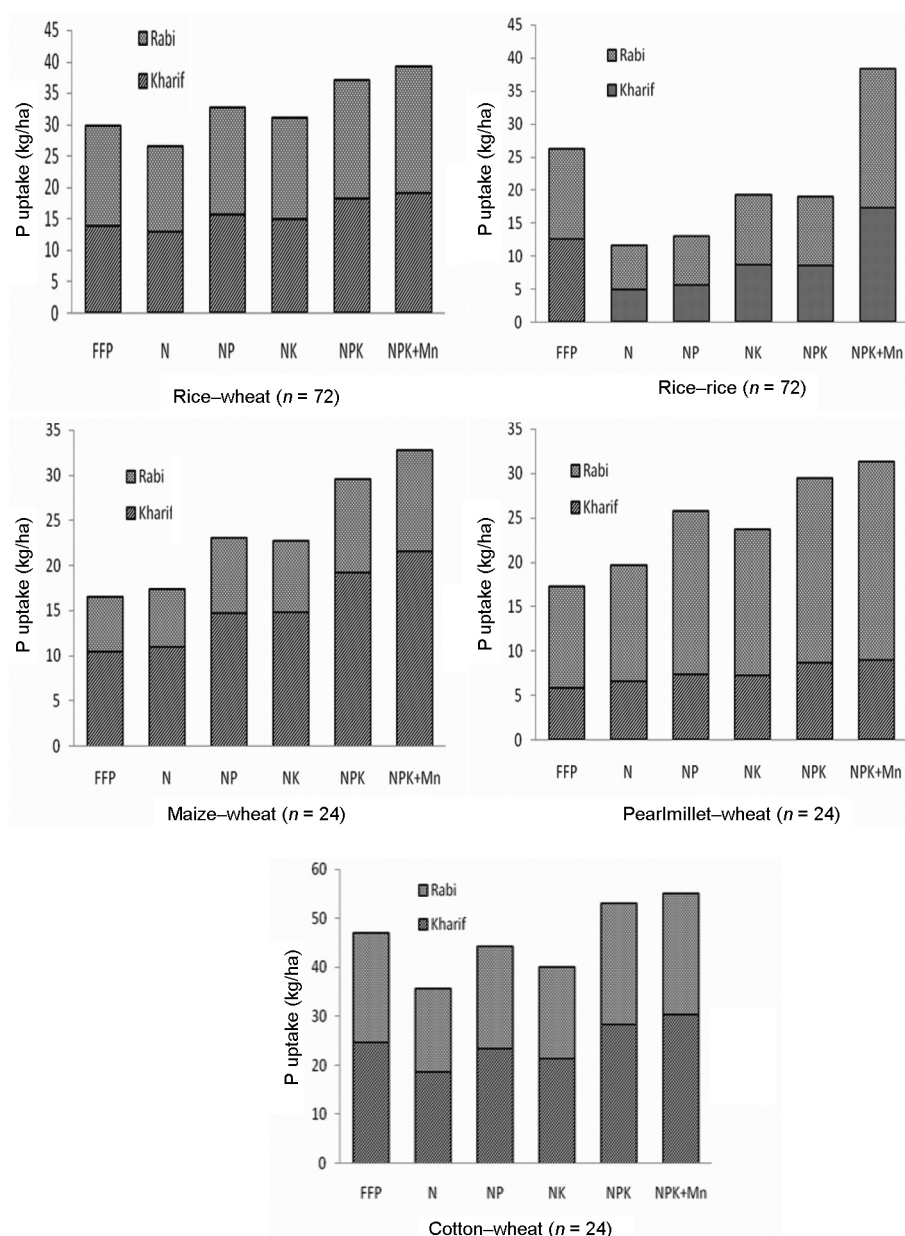


Figure 2. Phosphorus uptake under different nutrient management options (Source: Ref. 59).

for wheat at different locations. A tremendous increase in the agronomic efficiency of applied P (AE_P) in rice and wheat such as 38.6 to 70.2 kg grain kg^{-1} P and 22.7 to 37.4 kg grain kg^{-1} P respectively, was noted when all the deficient nutrients (macro and micro S, Zn, B) were applied for attaining high yield targets. In the on-farm studies also, partial factor productivity ($PFPP_P$) and AE_P were maximum with balanced NPK fertilization under different pre-dominant cropping systems (Table 3)^{58,59}. Conjunctive uses of S and Zn with P have pronounced effect on P responses and use efficiency in many crops at various locations of AICRP-IFS. Studies conducted on direct application of ground phosphate rock (GPR) on neutral Typic Ustochrept revealed that instead of applying

GPR at the recommended rate to each crop, heavy initial dressings at P rates recommended for 4–6 rice or wheat crops is a promising option. Inoculation with *A. awamori* culture, i.e. root-dipping of rice seedlings and seed treatment of wheat further improved P availability from GPR, annual productivity and net profits⁶⁰.

Analysis of multi-location long-term experiments (LTEs), conducted under AICRP-IFS indicated a highly significant ($P < 0.01$) increase in yield of rice with integrated use of fertilizers and manures, suggesting thereby the advantage of the integrated plant nutrient supply system (IPNS) over sole use of NPK fertilizers in sustaining crop yields⁶¹. As traditional organic manures are not available in adequate amounts, possibilities of inclusion

Table 3. Partial factor productivity and agronomic efficiency of P as influenced by balanced fertilization under different cropping systems

Cropping system	No. of trials	Partial factor productivity of P (kg grain kg ⁻¹ P)				Agronomic efficiency of P (kg grain kg ⁻¹ P)			
		I crop		II crop		I crop		II crop	
		with N	with NK	with N	with NK	with N	with NK	with N	with NK
Rice–rice system	1830	107.1	124.9	91.9	107.8	19.8	34.3	19.1	33.3
Rice–wheat system	1805	90.4	100.8	56.6	65.1	23.5	31.0	14.5	21.8
Pearl millet–mustard system	212	54.35	59.1	44.8	49	13.05	20.25	12.55	15.6
Maize–wheat system	1010	66.4	75.6	70.7	81.1	18.8	27.8	22.3	31.1
Soybean–wheat system	395	22.8	26.5	51.7	61.3	3.6	7.0	9.1	17.2
Pearl millet–wheat system	146	48.1	59.3	60.7	71.5	14.5	25.3	15.9	25.3
Cotton–wheat system	56	49.9	53.4	69.3	73	19.1	21.2	27.7	32.4
Rice–maize system	12	85.8	100.5	63.7	88.7	18.9	33.1	12.8	27.4

Source: Refs 58, 59.

of legumes in RWS may become a viable option for efficient P management strategies. Studies conducted by Dwivedi *et al.*⁶² revealed that forage cowpea grown during post-wheat summer on residual soil fertility increased the AE_P by 139% in the subsequent rice crop and by 55% in the following wheat crop, while improving the apparent recovery of P fertilizer by 9–13% in rice and wheat, besides raising wheat yield and soil organic matter content. In another study, substitution of rice by pigeon pea enhanced wheat yields and N and P use efficiency, owing to greater nutrient recycling through pigeon pea residues and reduction in sub-surface soil compaction (i.e. decrease in soil bulk density), leading to better root growth in succeeding wheat⁵⁷.

Recent studies conducted in the Western Plain zone by Singh *et al.*⁵⁷, indicated that around 61% large farmers (≥ 4 ha) burn rice residue partially or completely in their field. In such situations, use of Happy/Turbo seeder machine for wheat may prove a better option which recycles the whole rice residue without any yield penalty⁶³. Increasing soil organic carbon and N, P, K content, as well as the RWS productivity under residue recycling has already been reported by Yadav⁵⁶. The other options such as furrow irrigated raised bed (FIRB), permanent raised bed (PRB) and zero till seeding are promising options. Field experiments on Typic Ustochrept of Western IGP by Singh *et al.*⁵⁷ revealed that the economic optimum doses of fertilizer N and P for wheat in the pigeon pea–wheat system were smaller (128 kg N ha⁻¹ and 28 kg P ha⁻¹) under permanent raised bed (PRB) as compared to flat bed (FB) (152 kg N ha⁻¹ and 30 kg P ha⁻¹) owing to increased N and P supply, greater P use efficiency and a better crop growth environment along with higher Olsen P content under PRB planting.

Fertilizer P use efficiency

When P in a fertilizer or manure is added to the soil, it undergoes several biological and chemical reactions

which remove phosphate ions from the soil solution. However, this does not imply that the P becomes unavailable to plants. As measured by the direct method, rarely more than 25% of the added P fertilizer is taken up by the crop. The remainder of the P in the crop must come from soil P reserves, and this P must be returned if the existing level of plant-available P in the soil is to be maintained^{64–66}. It is frequently stated that P is used inefficiently in agriculture, with percentage recovery of P applied in fertilizers usually ranging between 10% and 20%. Johnston and Syers⁶⁷ suggested that such low efficiencies are primarily an artifact of the method used to calculate efficiency. When P efficiency is measured by the ‘balance method’ and when soil P levels are being maintained near the critical level, the efficiency of fertilizer P use frequently exceeds 90%. The above studies highlighted the importance of estimating use efficiency of applied P over a period of time, taking into account the accrued benefit of residual P in the subsequent crops.

Economics of P fertilization

Phosphorus is the costliest among different plant nutrients applied through fertilizers. Nonetheless, yield responses to fertilizer P are often substantial, making P application an economically remunerative option. On-farm studies conducted under AICRP-IFS revealed substantial net return on investment in P fertilizer (Rs 8.05–16.72 per rupee invested in fertilizer P₂O₅) in different cropping systems during 2004–2006 (Figure 3). The price hike by 2.5–3 times during the last two years, however, led to decline in economic returns (Rs 1.47–5.17 per rupee invested in P₂O₅). Among the cropping systems compared, lowest economic returns on P usage were obtained with pearl millet–mustard system. Although P application continues to be remunerative despite increased price of P fertilizer, the drop in economics of P fertilization in recent years underlined the significance of enhancing P use efficiency through adoption of appropriate management practices⁶⁸.

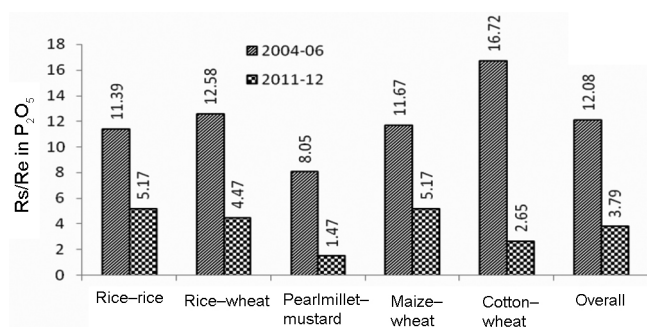


Figure 3. Change in economics (Rs Re⁻¹) net return invested on P due to increase in phosphatic fertilizers between 2003–2006 and 2011–12 (ref. 68).

Losses of P through erosion and runoff to the adjoining water bodies: pollution through eutrophication

Although the benefits of P in agriculture are evident, this element can be a pollutant if it moves from the site of application. The main concern is P transport from soils to streams, rivers, lakes and eventually oceans. Phosphorus transported from agricultural soils can promote *eutrophication* which is considered as one of the most pressing environmental problems. Loss of soil P to water bodies causes undesirable changes in the ecology of aquatic ecosystems, often with serious economic consequences. All forms of P within the soil system are subjected to a variety of pathways of transport at the soil profile, hill-slope, or catchment scale. Particulate and colloid P transport is most commonly associated with soil erosion, which arises from raindrop impact and overland flow. Additionally, when fertilizer or manure application is coincident with fast or energetic water flows, this will contribute to particularly high losses⁶⁹.

Phosphorus is lost from crop lands via erosion or runoff. Little attention has been paid to the management strategies for minimizing non-point movement of P in the landscape. As a result, non-point sources now account for a larger share of the nation's water quality problems than ever before. The main factors influencing P movement can be divided into transport and P source factors. Transport factors include the mechanisms by which P moves within a landscape. These are rainfall- and irrigation-induced erosion and runoff. Factors which influence the source and amount of P available to be transported are soil P content and rate and method of P applied in either mineral fertilizer or organic forms⁴⁰.

As runoff enters a stream channel and, ultimately, a water body, there is generally a progressive dilution of P load through water dilution and sediment deposition. Sources of particulate P in streams include eroding surface soil, plant material, stream banks, etc. As the finer-sized fractions of source material are preferentially eroded, the P content and reactivity of the eroded particulate material is usually greater than that of the source soil.

Minimizing eutrophication through efficient P management

Losses of P from cultivated lands could be minimized by adopting judicious P management strategies. Continuous P fertilization over the years at rates exceeding those of crop removal results in P build-up, often above the levels required for crop production. Once soil test P levels become excessive, further application of P will increase the potential for P movement while providing no further agronomic benefit. Accumulation of soil test P near the soil surface due to previous P application influences the concentration and loss of P in runoff⁷⁰. Highly significant linear relationships are frequently seen between the soil test P in the surface soil and dissolved P concentration in surface runoff. Adoption of soil test based P fertilization would, therefore, not only be economically viable but would also avoid its excessive accumulation in soil. Assessing the impact of P management through fertilizers and manures on P losses at field as well as watershed levels is important from both agronomic and environmental viewpoints⁷¹.

Future lines of research

- Better predictive understanding of P sorption and release behaviour of soils, including the hysteresis effect and the mechanisms of these processes is needed. In particular, more information on the rate and the amount of desorption of inorganic P from different Indian soils would be useful in adopting the suitable P-management practices under varying soil-crop-environment situations.
- Turnover rate of soil organic P is not well-understood, particularly under lowland rice soils. Information needs to be generated on the quantification of the pool-size and turnover of biomass P in soil for long-term P management strategies.
- Analytical methods used for soil testing for available P need careful assessment, especially for the lowland (submerged) rice soils. Possibility of including in the soil test values the contribution from organic P to the pool of soil available-P may also be explored.
- Interpretation of fertilizer response data based on soil test values appears to be inadequate. A complementary approach to soil testing may be the modelling approach, wherein previous P applications are considered while assessing the current available P status of the soils. For this to be operative, more intense research is necessary to characterize further the rates of reactions of P with soil, and the effect of soil properties on such rates.
- There is a need to formulate the P fertilizer recommendations for cropping sequence as a whole, rather than for individual crops in the rotation, considering the role of residual P towards meeting crop P demands.

- Research evidences suggest that plants infected with arbuscular mycorrhizae (AM) are capable of accessing poorly available P more effectively than the non-infected plants, but the mechanisms by which they do so are not clear. This needs to be understood thoroughly so as to explore the possibilities of AM-mediated P mobilization in the soil.
 - In view of dependence of Indian fertilizer industry on the import of raw materials or finished P fertilizer products and soaring market prices, emphasis needs to be laid on efficient utilization of indigenous low grade rock phosphates (RPs). Renewed research interest in relatively less investigated areas of P-enrichment of composts, heavy initial P application as RP, microbial dissolution of insoluble/sparingly soluble P, and development of nano-P fertilizers would be of great help in ensuring judicious P input to the crops.
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