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Phosphorus fractions -their key role in soil management

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Abstract

Phosphorus (P) is a critical macronutrient influencing soil fertility and crop productivity in India. In Indian soils, phosphorus exists in both organic and inorganic fractions, each differing in availability and mobility. The primary inorganic fractions include calcium-bound, iron-bound, and aluminum-bound phosphates, while organic phosphorus occurs mainly as inositol phosphates, phospholipids, and nucleic acids. Indian soils, being largely acidic or alkaline with low native phosphorus reserves, exhibit strong fixation tendencies that reduce available P. Management practices such as integrated use of fertilizers and organic amendments influence the distribution and transformation of these fractions. Studies indicate that phosphorus fractions vary with soil type, climatic conditions, and cropping systems, and their dynamics play an important role in sustaining long-term fertility of soil and productivity. Hence knowledge about the fractions contributes to a better understanding of phosphorus dynamics in soils and its implications for agricultural productivity and environmental sustainability.

Keywords: Phosphorus fractions, sustainability, organic and inorganic forms

Introduction

Phosphorus serves as a cornerstone for balanced fertilization in Indian agriculture. It plays a vital role in almost every biological process, being essential for energy generation, transfer, and storage through ATP and ADP, often referred to as the “energy currency” of living systems. In addition, phosphorus is a key constituent of cellular metabolism and serves as a structural element of nucleic acids, cell membranes, and other vital biomolecules (Wiedenhoeft, 2006). Phosphorus (P) is a vital nutrient for plant growth and plays a key role in the developmental processes of agricultural crops (Withers *et al.*, 2008). In soils, nearly two-thirds of inorganic phosphorus and about one-third of organic phosphorus remain unavailable, particularly in soils with variable charges. The efficiency of phosphorus utilization by crops is typically low, as a substantial fraction becomes fixed with iron (Fe), aluminum (Al), and calcium (Ca), greatly restricting its availability to plants (McBeath *et al.*, 2005) ^[11]. In fact, 70-90% of the phosphorus added to soil is immobilized, making it difficult for plants to absorb and utilize (Lei *et al.*, 2004) ^[4]. It is therefore important to consider both organic and inorganic P fractions for soil P fertility evaluation. It can serve as an indicator for proper nutrient management. Shen *et al.* (2004) ^[24] reported that studying phosphorus fractions offers an effective way to evaluate soil P availability and to understand the interconversion of phosphorus among different soil pools. Therefore, the present study was undertaken to assess the distribution of P fractions across various soil orders. Phosphorus is the tenth most abundant element in the earth's crust. About 200 minerals occurring in nature, have been reported to contain P with apatite group of minerals being the most important. Soil holds phosphorus in both organic and inorganic forms. Understanding these forms is crucial to determine how plants absorb phosphorus and how much of it moves through the environment. Among the major plant nutrients, phosphorus is the least mobile. Generally P is present predominantly in the inorganic form, with organic P content varying from 20-80% of the total P in the soil.

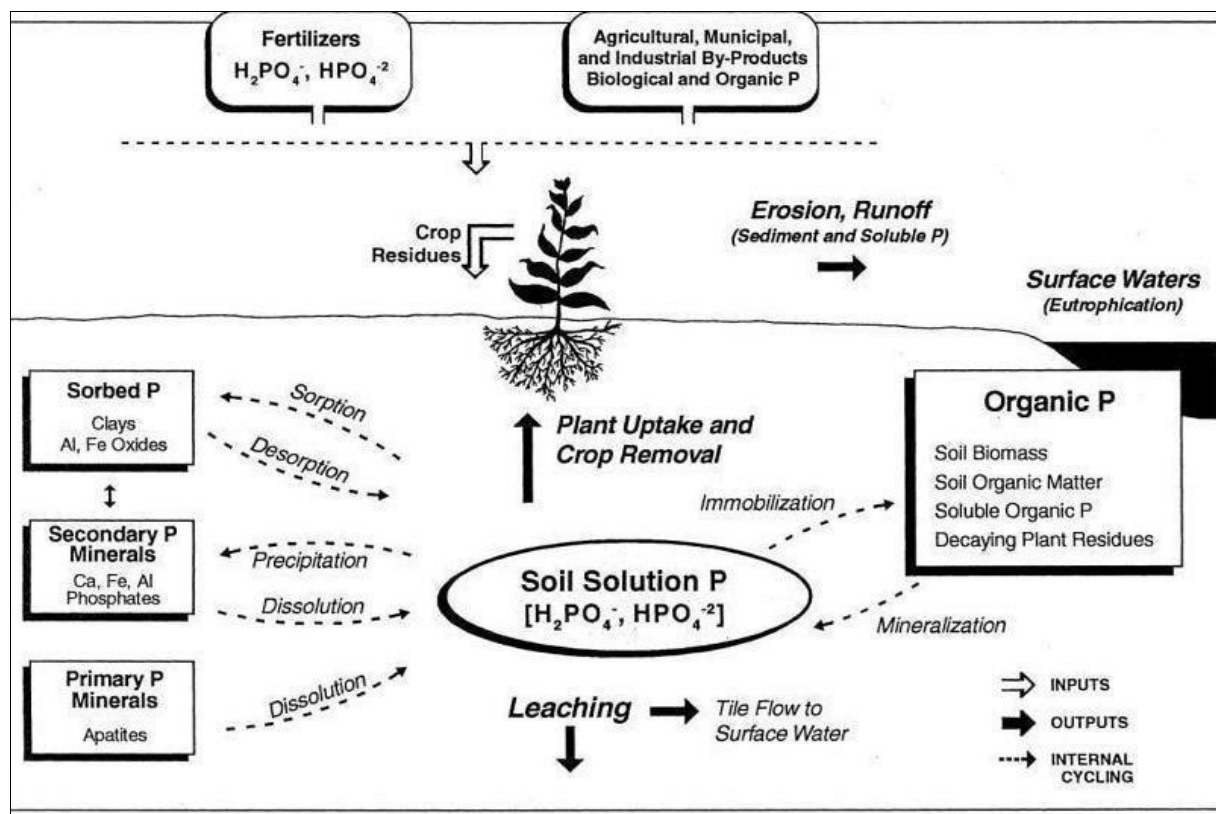


Fig 1: Forms of Phosphorus

The inorganic phosphates in soil comprise the (i) Iron and Aluminium phosphates (ii) calcium phosphates. The former predominate in acidic soils while the latter predominates in neutral and alkaline soils. The Al-P and Fe-P contents are generally higher in fertilized soils. Relatively less important inorganic P fractions include the occluded or the reductant soluble P. The soil organic P compounds may generally be classified into three groups, (i) inositol phosphates, (ii) nucleic

acids and (iii) phospholipids. Research on organic P suggests that the readily decomposable or soluble fractions of soil organic P is often important in supplying P to the plants in highly weathered soils. Mineralisation of organic P in soils is influenced by factors such as temperature, moisture, tillage etc. Of the total P content in soil a very small fraction is present in plant available form in the soil solution which generally do not exceed 0.1-0.2mg L⁻¹.

Table 1: Fractions of Phosphorus in soil

Category	Form	Examples/Compounds	Availability to Plants
Inorganic P	Soil Solution P	Orthophosphates (H_2PO_4^- , HPO_4^{2-})	Immediately available
	Labile P	Weakly adsorbed on clay/humus	Readily available (short-term)
	Non-labile (Fixed) P		Poorly available
	- Calcium-bound P (Ca-P)	Apatite, hydroxyapatite (alkaline soils)	Low
	- Iron-bound P (Fe-P)	Fe-phosphate (acidic soils)	Low
	- Aluminium-bound P (Al-P)	Al-phosphate (acidic soils)	Low
	- Occluded P	Trapped within Fe/Al oxides	Very low
Organic P	Inositol Phosphates	Phytate	Slowly available
	Phospholipids	Cell membrane components	Slowly available
	Nucleic Acids	DNA, RNA	Slowly available
	Humic-bound P	Stabilized in soil organic matter	Very low
Biological P	Microbial P	Present in microbial biomass	Available after microbial turnover
	Enzyme-bound P	Bound to phosphatases, phytases	Released gradually
Fertilizer P	Orthophosphates	From DAP, MAP, superphosphate	Immediately available
	Polyphosphates	Chain phosphates (fertilizer)	Slowly hydrolyze to orthophosphate

Table 2: Extraction of fractions of phosphorus (Patidar et al., 2019) ^[19]

Step	Reagent / Solution	Conditions	Extracted P Fraction
1	25 ml 1 N NH_4Cl	Shake 30 min → Centrifuge 5 min	Saloid-P (loosely bound P)
2	25 ml 0.5 N NH_4F	Shake 30 min → Centrifuge 5 min	Al-P (Aluminium-bound P)
3	Wash residue with 25 ml NaCl	—	—
4	25 ml 0.1 M NaOH	Shake 17 h → Centrifuge 5 min	Fe-P (Iron-bound P)
5	Wash residue with 25 ml NaCl	—	—
6	25 ml 0.1 M NaOH	Shake 1 h → Centrifuge 5 min	Occluded-P
7	Wash residue with 25 ml NaCl	—	—
8	25 ml 0.5 N H_2SO_4	Shake 1 h → Centrifuge 5 min	Ca-P (Calcium-bound P)

Fractionation studies of Phosphorus in soil-

Doddamani and Seshagiri Rao (1989) ^[2] investigated the forms of phosphorus in Karnataka soils and reported that Ca-P was the predominant fraction, contributing up to 19.5% of total P in Vertisols and up to 11.5% in Inceptisols. Fe-P accounted for 14.2%, 9.1%, 2.5%, and 2.4% of total P in Oxisols, Alfisols, Vertisols, and Inceptisols, respectively. The highest levels of reductant-soluble P were recorded in Oxisols, followed by Alfisols, Vertisols, and Inceptisols. Occluded-P and saloid-P contributed 2.9-3.0% and 0.5-0.6% of total soil P, respectively, across these soils.

Rao and Krishnamurthy (2007) ^[21] reported that in the soils of Khamman district, Andhra Pradesh, the concentrations of different Pi fractions varied as follows: saloid-P ranged from 13.5 to 78.4 mg kg⁻¹, Al-P from 45.0 to 499 mg kg⁻¹, Fe-P from 6.2 to 47.9 mg kg⁻¹, and Ca-P from 6.9 to 438.2 mg kg⁻¹.

Lungmuana *et al.*, (2012) ^[9] investigated the distribution of phosphorus in rice-growing red and laterite soils of West Bengal and found that the average contribution of various Pi fractions to total P followed the order: Fe-P (18.5%) > Al-P (7.9%) > Ca-P (5.8%) > saloid-P (0.8%).

Gupta *et al.*, (1999) ^[3] observed that use of P alone and in blend with FYM extended the total phosphorus content and distinctive phosphorus pools.

Dakhore reported that under unmanured cultivation, the utilization of inorganic P forms in sandy loam Entisols followed the order: Saloid-P > Al-P > Fe-P > Ca-P. Both forms of phosphorus were enhanced when nitrogen and potassium

applications were reduced.

Setia and Sharma (2007) ^[22] investigated that application of P @ 17.50 or 35 kg P ha⁻¹ increased all the forms of P in 22 years of maize-wheat cycles. The relative abundance of P fractions was in the order of saloid-P < Fe-P < Al-P < Ca-P.

Sukhvir Kaur (2015) ^[5] observed that the application of integrated fertilizers resulted in higher P fractions in very low and low gradient strips, which could be attributed to the acidic soil pH favoring the transformation of applied P into Al-P and Fe-P fractions.

Jakasaniya and Trivedi (2004) ^[4] observed that with increasing rates of P application, the fractions of S-P, Al-P, Fe-P, and Ca-P increased across different soils, while Org-P accumulated as a result of sorghum cultivation in all soils.

Nayak *et al.*, (2015) ^[14] stated that red-P ranged from a minimum of 79 kg ha⁻¹ in the control plot to a maximum of 152.48 kg ha⁻¹ under the 150% NPK treatment. The application of graded doses of NPK fertilizer led to an increase in Red-P compared to the control.

Chang *et al.*, (2004) ^[1] reported that in acidic soils, the initially superficial and loosely bound phosphates associated with Fe and Al oxides, which are available to plants, gradually undergo re-precipitation and transform into highly crystalline Fe- and Al-P forms that are unavailable to plants.

Ojo *et al.* (2015) ^[17] stated that variations in soil P fractions are strongly influenced by soil type. Differences in total P content among soil orders arise from the combined effects of parent material, weathering, and other pedogenic processes.

A comparison between phosphorus fractions in different soil orders and cropping systems

Table 3: Phosphorus fractions (kg ha⁻¹) in different soils (Patidar *et al.*, 2019) ^[19]

Sites	Saloid-P	Al-P	Fe-P	Occl-P	Ca-P	Res-P	Total-P
(V ₁)	10.36	18.75	11.12	12	47.74	32.84	132.82
(V ₂)	8.72	19.51	16.08	16.37	38.35	32.02	122.32
(V ₃)	12.46	24.48	13.71	17.62	31.99	38.35	129.62
(A ₁)	11.56	18.69	26.53	13.37	34.15	17.08	140.38
(A ₂)	9.74	25.27	28.02	18.65	32.89	18.79	145.37
(A ₃)	8.51	22.7	30.93	20.21	43.41	8.7	136.46
(I ₁)	7.11	19.73	12.03	16.75	28.33	26.62	134.57
(I ₂)	9.17	17.69	11.27	16.85	33.59	7.95	132.51
(I ₃)	10.55	19.54	12.04	15.82	30.12	22.11	134.17

Here V-Vertisols, A- Alfisols, I -Inceptisols

In (table 3) the distribution of phosphorus fractions varied across Vertisols (V), Alfisols (A), and Inceptisols (I). Calcium-bound P (Ca-P) was the dominant fraction in all soils, followed by Fe-P and Al-P, while Saloid-P contributed the least. Among soil orders, Alfisols (A1-A3) showed relatively higher Fe-P and Al-P contents compared to Vertisols and Inceptisols, indicating stronger P fixation by Fe and Al oxides. Vertisols (V1-V3) had

higher Ca-P, reflecting their calcareous nature, whereas Inceptisols maintained more balanced fractions but comparatively lower Ca-P. Total P was highest in Alfisols (145.37 kg ha⁻¹ in A2) and lowest in Vertisols (122.32 kg ha⁻¹ in V2). Overall, the results highlight soil-order-specific differences in P fractionation, with Vertisols dominated by Ca-P, Alfisols by Fe-P and Al-P, and Inceptisols showing intermediate levels.

Table 4: Distribution of Soil P fractions under different cropping patterns (Tiwari *et al.*, 2012)

Crop pattern	Depth of soil(m)	Organic C (g kg ⁻¹)	Calcium carbonate (gkg ⁻¹)	OrganicP (mgkg ⁻¹)	Inorganic P fractions(mg-kg ⁻¹)				AvailableP (kg ha ⁻¹)
					Saloid-P	Ca-P	Fe-P	Al-P	
Rice-wheat	0.00-0.15	3.4	4.5	78	20	182	72	40	8.9
	0.15-0.30	2.8	4.8	63	15	201	80	38	7.6
Maize-wheat	0.00-0.15	3.8	4.8	92	29	190	92	44	9.0
	0.15-0.30	3.0	5.3	66	18	210	83	42	7.5
Rice-potato	0.00-0.15	3.8	4.7	98	34	177	78	41	10.8
	0.15-0.30	2.6	5.2	60	13	200	85	36	7.8
Maize-potato	0.00-0.15	3.6	3.9	92	25	180	83	42	11.0
	0.15-0.30	2.8	4.5	62	18	205	88	35	8.0
Rice-pea	0.00-0.15	3.2	3.9	76	24	175	88	34	10.0

	0.15-0.30	2.6	4.6	58	15	198	96	40	8.2
Maize-pea	0.00-0.15	3.4	4.9	94	23	180	93	46	10.4
	0.15-0.30	2.7	5.3	60	15	196	90	43	8.4
Rice-cauliflower	0.00-0.15	4.0	4.5	96	38	195	80	35	9.6
	0.15-0.30	3.1	5.6	66	20	212	86	34	8.0
Maize-cauliflower	0.00-0.15	3.9	4.9	90	40	190	85	42	10.0
	0.15-0.30	3.0	5.7	72	21	214	78	38	8.6
Okra-potato	0.00-0.15	3.5	5.0	80	25	175	90	36	11.0
	0.15-0.30	2.7	5.7	62	17	117	86	30	9.0
Okra-tomato	0.00-0.15	3.6	4.9	87	24	180	82	33	10.0
	0.15-0.30	2.4	5.1	56	17	200	78	30	8.3

In this (table 4) it was clearly observed that organic carbon content declined with increasing soil depth, while calcium carbonate content showed an upward trend across all cropping patterns. In the surface layer, organic carbon ranged from 3.2 to 4.0 g kg⁻¹, whereas in the subsurface layer it ranged from 2.4 to 3.1 g kg⁻¹. Calcium carbonate content varied between 3.90 and 5.00 mg kg⁻¹ in the respective layers. Overall, soils under all cropping patterns were characterized by low organic carbon status and classified as non-calcareous. It was observed that the organic P fraction was consistently higher in the surface layer than in the subsurface soils across all cropping patterns, mainly due to greater organic matter content in the surface horizon. Organic P ranged from 55 to 68 mg kg⁻¹ in surface soils and 37 to 48 mg kg⁻¹ in subsurface soils. Among the inorganic P fractions, Ca-P was the dominant form, followed by Fe-P, Al-P, and Saloid-P under all cropping systems. Saloid-P content varied from 20 to 40 mg kg⁻¹ in the surface layer and 13 to 21 mg kg⁻¹ in subsurface soils, with consistently higher values in surface horizons. The maximum saloid-P was recorded under the maize-cauliflower sequence, followed by rice-cauliflower. Interestingly, Ca-P increased with soil depth across all patterns, with the highest Ca-P content under okra-potato and the lowest under rice-pea and maize-pea cropping sequences.

Chang *et al.*, (2004) ^[1] observed that the organic-P content declined up to 90 DAS but increased again at crop harvest across all treatments. This reduction could be attributed to microbial mineralization and crop uptake, while the subsequent increase at harvest was likely due to enhanced plant growth and the accumulation of organic matter in the soil, which contributed to higher organic-P levels.

Patel *et al.* (2024) ^[18] reported that phosphorus application had a significant effect on Red-P levels, which ranged from 80.00 to 91.04 mg kg⁻¹ in 2020-21 and from 80.84 to 93.62 mg kg⁻¹ in 2021-22. Application of 90 kg P ha⁻¹ markedly increased Red-P compared to 30 and 0 kg P ha⁻¹. Across both years, Red-P content rose with higher phosphorus levels, reaching 91.04, 93.62, and 92.33 mg kg⁻¹ under 90 kg P ha⁻¹. Phosphorus fertilization at 30, 60, and 90 kg ha⁻¹ enhanced Red-P by 5.59%, 10.87%, and 14.10% over the control, respectively. The lowest mean Red-P levels (80.00, 80.84, and 80.92 mg kg⁻¹) were consistently recorded in P-omitted (Po) plots.

Majumdar *et al.*, (2007) ^[12] reported that organic phosphorus (Org-P) contributed between 48.90 and 53.70 percent to total phosphorus (T-P). They also observed a significant increase in saloid-P (S-P), aluminum-bound P (Al-P), iron-bound P (Fe-P), and calcium-bound P (Ca-P), while reductant-soluble P and occluded-P fractions showed a decline.

Nunes *et al.*, (2020) ^[15] investigated the effects of long-term tillage and fertilizer practices on soil phosphorus fractions. They found that, compared to conventional tillage, no-tillage resulted in greater accumulation of inorganic P (Pi) in labile fractions, while organic P was more strongly associated with protective aggregates. Additionally, the use of reactive rock phosphate

under no-tillage increased the Ca-P fraction compared to the use of triple superphosphate under conventional tillage, with this increase being more pronounced when fertilizers were applied by broadcasting.

Mahawar *et al.* (2022) ^[13] reported that the application of FYM at 5 t ha⁻¹ significantly enhanced the proportion of the saloid-P fraction. It is important to note that saloid-P corresponds to the form of phosphorus that is readily available for plant uptake.

Tiwari and Vats reported that the availability of phosphorus in soil improved significantly with the application of 100% NPK along with organic matter. The addition of organic manure enhanced available phosphorus through the involvement of cations such as Ca²⁺, Mg²⁺, Fe³⁺, and Al³⁺, which play a key role in phosphorus fixation.

Yang *et al.* (2015) ^[7], in their long-term study on phosphorus fertilizers, observed that the addition of organic matter markedly enhanced the residual fraction as well as other organic fractions (labile and partially labile), while no change was detected in the resistant form. In contrast, the application of mineral fertilizers, consistent with their findings, had no significant effect on any group of organic fractions.

Majhi *et al.* (2003) ^[10] reported that the continuous inclusion or omission of certain secondary nutrients (S) and micronutrients (Zn and B) had no significant impact on grain yield. However, the results clearly indicated that the application of FYM had a notable positive effect on grain yield in both seasons.

Nwoke *et al.* (2004) ^[16] observed variations in different inorganic-P fractions in soils under diverse management practices, with phosphorus depletion ranging from 33% to 129% over an 11-year period.

Sharpley *et al.* (2004) ^[23] reported that continuous application of organic fertilizers increases soil organic phosphorus fractions. In our study, the variations were most evident in the upper two soil layers (0-20 and 20-40 cm), whereas the 40-60 cm layer generally showed the lowest values across most treatments and fractions. These differences were statistically significant, particularly in the manure-applied treatments (IV and V).

Liao *et al.*, (2020) ^[8] stated that crop roots release substantial amounts of organic compounds that help mobilize sparingly available phosphorus (P) in soils. This includes the exudation of protons, malate, and citrate into the rhizosphere, which solubilize insoluble P forms. Additionally, roots secrete acid phosphatase enzymes that hydrolyze organic phosphorus (Po) into inorganic phosphorus (Pi), making it available for plant uptake.

Conclusion

Phosphorus fractions play a crucial role in soil management, influencing soil fertility, plant nutrition and ecosystem health. Understanding the different phosphorus fractions and their dynamics is essential for optimizing fertilizer use, improving soil fertility, sustainable agriculture, environment protection. These studies have highlighted the importance of phosphorus

fractionation in determining phosphorus availability, soil fertility and crop productivity. It is concluded that by increasing the level of phosphorus there is a significant increase in growth and yield parameters of the plants and even in long term experiments continued application of phosphorus leads to an increase in all fractions of phosphorus in soils. It also shows that different levels of N, P, K also affect the different fractions of phosphorus in soil.

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