



RESEARCH ARTICLE

Influence of phosphorus levels on phosphorus fractionation and transformation in Inceptisols

Varsha S¹, Ravindran Angelin Silviya¹, Kaliyaperumal Anbukkarasi² & Rajasekaran Nagajothi³

¹Department of Soil Science, Sri Ramasamy Memorial (SRM) College of Agricultural Sciences, SRM Institute of Science and Technology, Baburayanpettai, Chengalpattu 603 201, Tamil Nadu, India

²Department of Natural Resource Management, Sri Ramasamy Memorial (SRM) College of Agricultural Sciences, SRM Institute of Science and Technology, Baburayanpettai, Chengalpattu 603 201, Tamil Nadu, India

³Section of Biochemistry and Crop Physiology, Sri Ramasamy Memorial (SRM) College of Agricultural Sciences, SRM Institute of Science and Technology, Baburayanpettai, Chengalpattu 603 201, Tamil Nadu, India

*Correspondence email - vs1520@srmist.edu.in, angelinr@srmist.edu.in

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Abstract

Phosphorus (P), a crucial macronutrient for plant growth, is severely limited to Inceptisols due to its fixation by calcium (Ca), iron (Fe) and aluminium oxides (Al_2O_3), which renders it insoluble and unavailable for plant uptake. An experimental investigation involving soil incubation was conducted to examine the transformation of phosphorus (P) fractions in Inceptisol soil. Seven treatments were evaluated: absolute control, control and potassium dihydrogen phosphate (KH_2PO_4) at 20, 40, 60, 80 and 100 ppm. Soil samples were collected at 0, 10, 20, 30, 40 and 50 days of incubation. Phosphorus fractions and total P were determined using appropriate analytical methods, including the molybdenum blue spectrophotometric method for total P. Phosphorus fractions were significantly affected by both P concentration and incubation period. Soluble P initially increased and subsequently decreased, indicating its transformation into less-soluble forms. Stable P fractions, including calcium phosphate, iron-bound P and non-labile P gradually increased during the incubation period. Maximum P availability was observed on day 20. Principal component analysis (PCA) confirmed distinct clustering of the stable P fractions. Correlation analysis revealed strong positive relationships among the stable P fractions, whereas negative relationships were observed between soluble and stable P fractions. These findings indicate that the Inceptisol had a strong capacity to fix applied P into stable forms, suggesting that split or slow-release P fertilisation strategies, timed according to crop demand, may be necessary to sustain plant-available P and improve fertiliser-use efficiency in such soils.

Keywords: correlation analysis; Inceptisol; KH_2PO_4 ; phosphorus behaviour; phosphorus fractions; principal component analysis

Introduction

Phosphorus (P) is one of the critical elements required for various physiological and biochemical processes in plant cells, including nutrient transport, photosynthesis, respiration, cell division and root development. It is present in several biological compounds, such as ATP, phospholipids and nucleic acids. Although P plays a crucial role in physiological and biochemical processes, it is generally considered a limiting nutrient in soils because of its low solubility in mineral and organic forms, resulting in low bioavailability to plants. Several soil properties, including pH, mineral composition and adsorption-desorption processes, influence P availability (1–6).

In tropical and subtropical Inceptisols, P immobilisation through chemical interactions acts as an important regulatory mechanism controlling P availability. Phosphate ions tend to bind to the surfaces of iron (Fe) and aluminium oxide (Al_2O_3) minerals under acidic conditions, forming insoluble Fe–P and Al–P compounds. Conversely, the precipitation of Ca–P compounds are favoured under alkaline conditions (3, 7–10). Although phosphate fertilisers such as dihydrogen phosphate (KH_2PO_4) can be used to increase P

availability, P immobilisation through adsorption and precipitation occurs rapidly, reducing its bioavailability and increasing the risk of P accumulation as poorly available legacy P in the soil (11–14). The KH_2PO_4 was selected as the P source for this incubation study because it is a fully water-soluble, chemically well-defined salt that supplies P in a readily available form without the accompanying nitrogen (N), sulphate or organic carbon introduced by fertilisers such as diammonium phosphate or single superphosphate. Therefore, it allows P transformation to be examined independently of confounding effects associated with other nutrients or organic matter (15). In this regard, improving nutrient-use efficiency and sustainably managing soil fertility require an understanding of the transformation and distribution of P fractions in Inceptisols. The objective of this study was to investigate the dynamics of P fractions in Inceptisol soil under different P addition rates and incubation periods. Specifically, the objectives were to (i) characterise different P fractions using the sequential extraction method (8, 16); (ii) evaluate the effects of P addition rates and incubation duration on P transformation through colorimetric determination using the molybdenum blue–ascorbic acid method (17) and (iii) examine the

relationships among P fractions using statistical approaches, including principal component analysis (PCA), correlation analysis and analysis of variance (ANOVA). The findings are expected to provide deeper insights into P transformation mechanisms and contribute to the development of improved P management strategies for Inceptisol soils (3, 14, 18, 19).

Materials and Methods

Experimental sites and soil sampling

Soil samples (0–15 cm depth) were collected from an agricultural plot classified as Inceptisol at SRM College of Agricultural Sciences (SRMCAS), Vendhar Nagar, Baburayanpettai, Elapakkam, Maduranthagam, Chengalpattu, Tamil Nadu, India. The farm is located at approximately 12.385379° N latitude and 79.741964° E longitude, at an elevation of approximately 50 m above mean sea level. The site experiences a hot, sub-humid tropical climate typical of coastal Tamil Nadu, with mean annual rainfall concentrated during the Northeast monsoon (October–December). Maximum temperatures range from 33–38 °C during summer (April–June), whereas winter (December–February) is relatively cooler and drier, with temperatures ranging from 20–28 °C. Composite soil samples were collected from multiple locations across the field, thoroughly mixed and transported to the laboratory for further analysis. The samples were air-dried at ambient temperature (25 ± 2 °C) for 5–7 days. Plant residues, roots and gravel were removed and the soil was gently crushed using a wooden mallet to minimise disturbance to the natural soil aggregates and passed through a 2 mm sieve. The processed soil was thoroughly homogenised and stored in labelled polyethylene bags until further analysis.

Preliminary soil characteristics

Preliminary analyses were conducted to characterise the initial soil properties. Soil pH and electrical conductivity (EC) were determined in a 1 : 2.5 soil-to-water suspension using a digital pH meter and conductivity meter respectively. These parameters are important indicators of P dissolution and transformation in soils. Particle-size distribution was determined using the international pipette method, organic carbon by the Walkley-Black wet-oxidation method, available P by the Olsen sodium bicarbonate method and exchangeable Ca and extractable Fe and aluminium by ammonium acetate and dithionite–citrate–bicarbonate extraction respectively (18). These baseline properties are essential for interpreting P transformation because clay content, organic carbon and reactive Fe and Al oxides are well-established determinants of P sorption and fractionation in tropical and subtropical soils (3, 5, 10). The physicochemical characteristics of the initial soil are presented in Table 1.

Experimental design and treatments

The experiment followed a factorial completely randomised design (FCRD), with P concentration and incubation period as the two factors. The seven treatments are detailed in Table 2. Each treatment was replicated three times to ensure statistical reliability.

Incubation procedure

Incubation containers were filled with 100 g of air-dried soil. Preparation of KH_2PO_4 stock solution and application to soil: A P stock solution containing 1000 mg P L^{-1} was prepared by dissolving 4.39 g of KH_2PO_4 , oven-dried at 60 °C for 1 hr, in distilled water and making the final volume up to 1 L. Treatment solutions containing

Table 1. Physicochemical characteristics of the initial Inceptisol soil sample

Parameter	Unit	Value	Method
pH (1 : 2.5 soil : water)	-	7.50	Digital pH meter
Electrical conductivity (EC)	dS m^{-1}	0.80	Digital conductivity meter (1 : 2.5)
Texture	-	Clay	Feel method
Organic carbon	%	0.60	Walkley-Black wet oxidation
Available P (Olsen)	kg ha^{-1}	84	NaHCO_3 extraction (13)
Exchangeable Ca	cmolc kg^{-1}	9.2	1 N ammonium acetate extraction
Extractable Fe	mg kg^{-1}	29.5	Dithionite–citrate–bicarbonate extraction
Extractable Al	mg kg^{-1}	23.8	Dithionite–citrate–bicarbonate extraction

Table 2. Treatment details used in the incubation experiment

Sl. No	Treatment	Details
1	T ₁	Absolute control (soil alone without water and phosphorus)
2	T ₂	Control (soil + distilled water)
3	T ₃	20 ppm phosphorus
4	T ₄	40 ppm phosphorus
5	T ₅	60 ppm phosphorus
6	T ₆	80 ppm phosphorus
7	T ₇	100 ppm phosphorus

20, 40, 60, 80 and 100 mg P L^{-1} were prepared by transferring 2, 4, 6, 8 and 10 mL of the stock solution respectively, into separate volumetric flasks and making the volume up to 100 mL with distilled water.

For each treatment, 100 mL of the respective P solution was uniformly applied to 100 g of air-dried soil. The control treatment received 100 mL of distilled water, whereas the absolute control received no solution. During incubation, soil moisture was maintained at field capacity by regularly adding distilled water. The containers were covered with perforated lids to facilitate ventilation, minimise contamination and retain moisture.

Soil samples were collected at predetermined time points of 0, 10, 20, 30, 40 and 50 days after treatment application. At each sampling time, a soil sample was collected from each treatment and analysed for P fractions.

A 50-day incubation period with sampling at 10-day intervals was selected because phosphate sorption in soil is a two-stage process. An initial rapid reaction, during which P binds to reactive surface sites, occurs within hours to a few days, followed by a slower, diffusion-controlled stage in which P penetrates mineral lattices and forms more stable Iron-bound phosphorus (Fe–P), aluminium-bound phosphorus (Al–P) and calcium-bound phosphorus (Ca–P) associations over subsequent weeks (4). Sampling at 10-day intervals over 50 days was therefore considered sufficient to capture both the rapid initial increase in soluble P and its subsequent transformation into moderately labile and non-labile fractions, consistent with incubation periods used in comparable P-fractionation studies (12, 20).

Phosphorus fractions

The sequential extraction method was developed for estimating P fractions (8, 16). By using the above method, P was classified into several groups based on its solubility and chemical relationship (8).

Phosphorus fractions in soils

Fraction of inorganic phosphorus

a) Soluble and loosely bound phosphorus (Sol-P), obtained by

- extracting with ammonium chloride
- b) Al-P, obtained by extracting with ammonium fluoride
- c) Fe-P, obtained by extracting with sodium hydroxide
- d) Reductant soluble phosphorus (Red-P), obtained by extracting with sodium dithionite-citrate-bicarbonate
- e) Ca-P, obtained by extracting with sulfuric acid

Phosphorus fractions in soil organic matter

- a) Labile organic P
- b) Moderate labile organic P
- c) Non-labile organic P

Phosphorus was sequentially extracted following the modified standard procedure (8, 16). Briefly, 1 g of air-dried soil was extracted with the respective extractants by shaking at 120 rpm. Soluble and loosely bound phosphorus (Sol-P) and Al-P were extracted with 50 mL of the respective extractant for 10 min. Iron-bound phosphorus (Fe-P) was extracted with 50 mL for 17 hr, Ca-P with 25 mL for 1 hr and labile organic phosphorus (Lab-P) with 50 mL for 16 hr. Moderately labile organic phosphorus (Mod-Lab-P) and non-labile organic phosphorus (Non-Lab-P) were each extracted with 50 mL for 17 hr. Reductant-soluble phosphorus (Red-P) was extracted by heating the soil-extractant mixture with dithionite-citrate-bicarbonate reagent at 85 °C for 15 min. Following each extraction, the suspensions were centrifuged at 10000 rpm for 10 min and the supernatants were collected for P determination.

Determination of phosphorus content

Phosphorus content in each extract was determined according to the standard method, commonly referred to as the molybdenum blue method (17). The method is based on the formation of a blue-coloured phosphomolybdate complex through the reaction of phosphate with ammonium molybdate under acidic conditions, followed by reduction with ascorbic acid. The P concentration was determined spectrophotometrically at 880 nm against a standard calibration curve prepared using KH_2PO_4 .

Statistical analysis

The collected data were subjected to appropriate statistical analyses. Analysis of variance (ANOVA) was performed to determine the effects of P treatment, incubation period and their interaction on the different P fractions. Treatment means were compared using Duncan's multiple range test (DMRT) at the 5 % significance level. Principal component analysis (PCA) was performed to identify the dominant variables influencing P dynamics and to assess relationships among the different P fractions. Correlation analysis was conducted to determine the strength and direction of associations among P fractions and incubation duration.

Results and Discussion

Impact of phosphorus levels and incubation time on soil phosphorus fractions

Phosphorus application rate and incubation duration significantly affected P fractionation in the Inceptisol soil. The ANOVA showed that all measured P fractions, including Sol-P, Al-P, Fe-P and Red-P, differed significantly ($p \leq 0.001$) among P treatments, incubation periods and their interaction. These results indicate that P transformation in this soil was jointly governed by the amount of P

applied and the duration of soil contact, with the fractions continuing to change throughout the incubation period rather than reaching an immediate steady state, in agreement with earlier reports (12, 21).

Phosphorus fractions increased consistently with increasing application rate, as confirmed by Duncan's multiple range test. The absolute control and control treatments recorded the lowest values, whereas the 100-ppm treatment recorded the highest values, followed by 80, 60, 40 and 20 ppm treatments in descending order. Fe-P increased from 15.91–28.37 mg kg⁻¹, Al-P from 16.98–30.48 mg kg⁻¹ and Red-P from 15.23–26.71 mg kg⁻¹, while mean soluble P increased from 18.21 mg kg⁻¹ in the absolute control to 31.16 mg kg⁻¹ at 100 ppm. These trends confirm that higher P application rates substantially increased P concentrations across the measured soil fractions (22, 23).

Effect of incubation and phosphorus interaction

Phosphorus fractions increased progressively up to 20 days of incubation, after which their concentrations either stabilised or gradually declined, reflecting the influence of incubation duration on P transformation. The highest mean concentrations of soluble phosphorus (27.51 mg kg⁻¹), Al-P (26.29 mg kg⁻¹), Fe-P (25.15 mg kg⁻¹) and Red-P (23.68 mg kg⁻¹) were recorded at 20 days. Beyond this point, the P fractions gradually declined, suggesting that P initially accumulated in more available forms before being converted into less-available forms through fixation and precipitation, consistent with previous findings (2, 6, 24). The interaction between P concentration and incubation period had a greater influence than either factor alone. At 20 days, the 100-ppm treatment recorded the highest concentrations of soluble P (35.70 mg kg⁻¹), Al-P (34.40 mg kg⁻¹), Fe-P (33.43 mg kg⁻¹) and Red-P (31.73 mg kg⁻¹). This indicates that the highest P availability occurred under this specific combination of P concentration and incubation duration, a pattern also reported in previous studies (12) (Fig. 1).

Principal component analysis of phosphorus fraction dynamics

To examine the interrelationships among P fractions and their transformation behaviour, PCA was performed. The first principal component (Dim1) accounted for 94.3 % of the total variance, while the second component (Dim2) accounted for 5.3 %, together explaining 99.6 % of the variability in the dataset.

In the PCA biplot, Ca-bound, Fe-bound, labile, non-labile, reductant-soluble and Al-P fractions clustered closely on the positive side of Dim1, indicating coordinated changes among these fractions as P was progressively retained by soil mineral surfaces. In contrast, labile P was separated slightly along Dim2, consistent with its role as a relatively short-lived transitional pool that may decline as P is transferred to more stable forms (23).

From an agronomic perspective, the close clustering of the stable fractions along Dim1 suggests that, once P begins to become immobilised in this soil, it is retained through related mineral-associated processes involving Fe and Al oxides and, to a lesser extent, Ca. This has practical implications for P fertiliser management because labile P appears to constitute a relatively transient pool. Therefore, repeated smaller applications timed according to crop demand may be more effective than a single large basal application in Inceptisols with strong P-fixation capacity (Fig. 2).

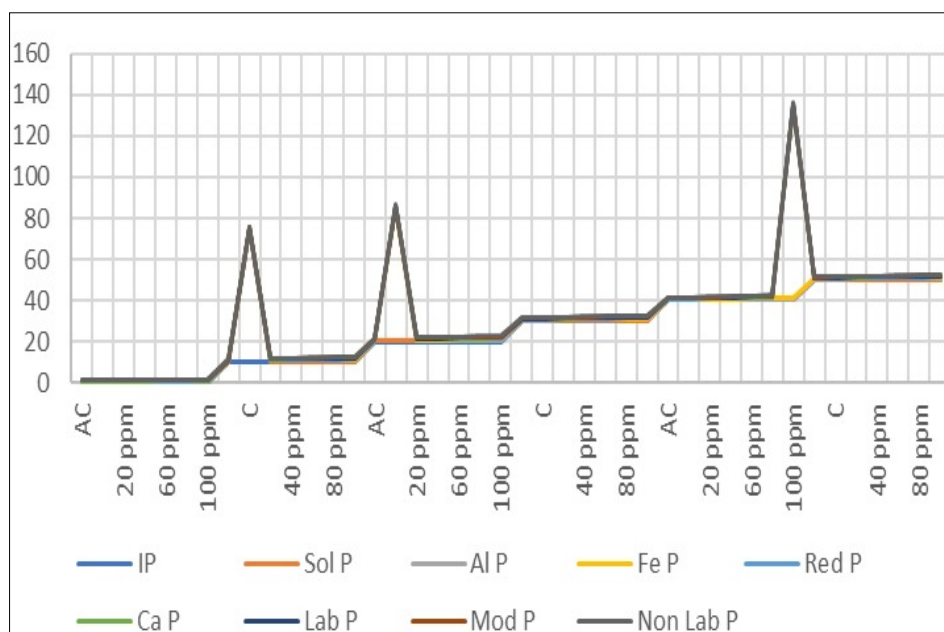


Fig. 1. A graph representing variation in the levels of various phosphorus fractions depending on treatment and incubation period, illustrating changes in soil phosphorus dynamics.

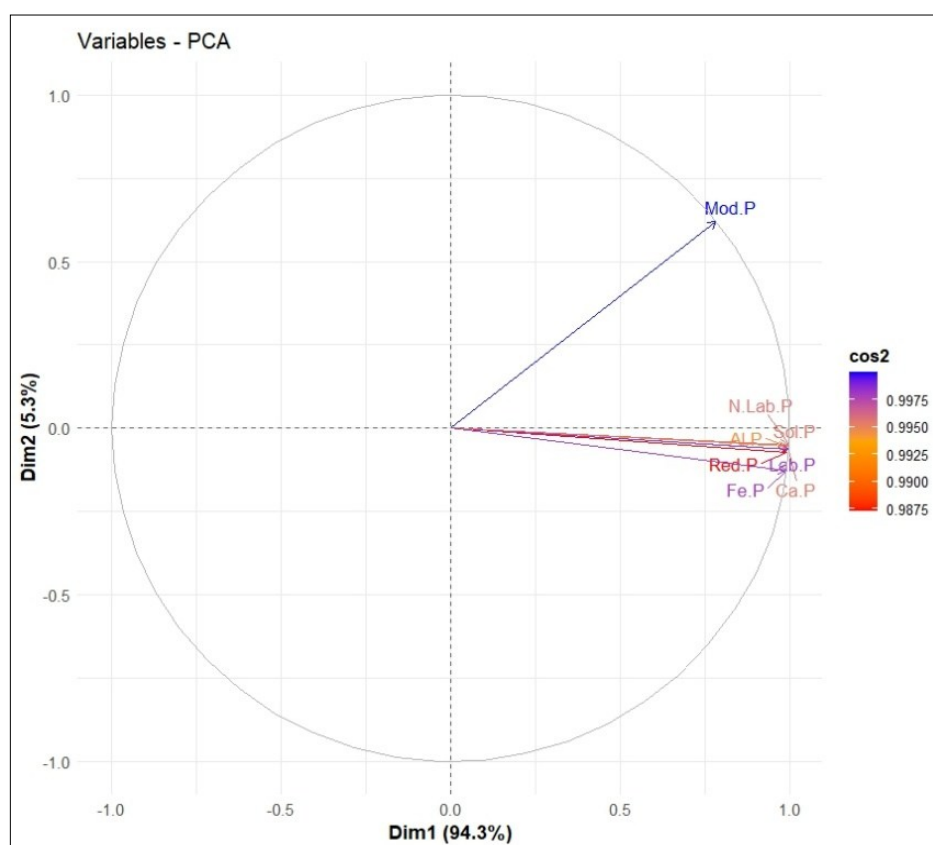


Fig. 2. Principal component analysis (PCA) biplot showing the relationship among different phosphorus fractions in soil, where Dim1 (94.3 %) and Dim2 (5.3 %) explain the total variation.

Phosphorus percentage correlations

Correlation analysis revealed highly significant positive correlations among most P fractions. The formation and stabilisation of relatively stable P pools were strongly associated with Ca-P, Fe-P, labile P, non-labile P and Al-P, with high positive correlation coefficients ($r = 0.98$ – 1.00). In contrast, relatively weak positive correlations ($r = 0.70$ – 0.75) were observed for the more labile P fractions, indicating their intermediate behaviour during P transformation.

Because several correlation coefficients approached the theoretical maximum of 1.00, the possibility of multicollinearity

among the stable P fractions should be considered. Such strong correlations are plausible because Ca-P, Fe-P, labile P and non-labile P represent sequentially extracted, chemically related pools that may respond similarly to P addition and incubation. Thus, their strong correlations may reflect a common underlying process involving the progressive retention and redistribution of applied P among soil P pools. Future regression-based modelling involving these fractions should therefore account for potential multicollinearity, for example, through variable selection or the use of PCA scores rather than highly correlated raw variables as predictors.

Significant negative correlations were observed between soluble P and the other P fractions, indicating an inverse association between readily available P and the more stable P pools. In addition, P stabilisation increased with incubation duration, as indicated by the positive correlations between stable P fractions and incubation period. Similar relationships have been reported in previous studies (2, 23). However, these correlations indicate associations among P fractions and do not, by themselves, provide direct evidence of specific transformation pathways or mechanisms (3, 5) (Fig. 3).

Transformation and stabilisation of phosphorus in Inceptisols

The results indicate a gradual conversion of P applied as KH_2PO_4 into relatively stable P fractions, particularly Fe-P, Ca-P and non-labile P. This transformation pattern was supported by the results of ANOVA, PCA and correlation analyses. The observed behaviour reflects the underlying chemistry of phosphate retention in Inceptisols.

Under the acidic to near-neutral conditions typical of these soils, phosphate ions initially adsorb onto the surfaces of Fe and Al_2O_3 through rapid surface reactions. With time, surface-bound phosphate can undergo ligand exchange with structural hydroxyl ($-\text{OH}$) groups, forming stronger inner-sphere Fe-O-P and Al-O-P complexes (3, 10). Where exchangeable Ca is present, phosphate may additionally precipitate as calcium phosphate compounds. Continued ageing of Fe-P, Al-P and Ca-P-associated forms can progressively result in occluded and less-labile P that is not readily extractable (5, 8).

The significant positive relationships among the stable P fractions, together with the significant negative relationships between soluble P and these fractions, are consistent with progressive P retention through adsorption, ligand exchange, precipitation and occlusion. These findings indicate that the studied

Inceptisol has a strong capacity to retain applied P over time, consistent with previous studies (12, 22, 23).

Implications for phosphorus fertiliser management in Inceptisols

These findings have important implications for P fertiliser management in Inceptisols. Because soluble P availability peaked approximately 20 days after application and subsequently declined as P was redistributed into Fe-P, Al-P and Ca-P fractions, a single basal application of a water-soluble P fertiliser such as KH_2PO_4 may not sustain plant-available P throughout the cropping season in this soil type. Split applications, band placement to reduce soil-fertiliser contact and the use of slow-release or organically complexed P sources may therefore improve P-use efficiency and reduce the accumulation of poorly available legacy P (3, 12, 14).

In addition, indices such as the degree of P saturation and the relative proportions of labile, moderately labile and occluded P have been shown to be useful for assessing P availability and the risk of P loss to water bodies (14). Incorporating such indices into future field-scale studies could help translate the present incubation-based findings into practical, site-specific fertiliser recommendations for Inceptisol-dominated cropping systems.

The present study was conducted under controlled laboratory incubation conditions using a single Inceptisol; therefore, the findings should be interpreted cautiously when extrapolating them to field conditions. Although the sequential extraction method provides valuable information on operationally defined P pools, these fractions do not necessarily correspond to discrete mineral phases. Future studies should validate these findings under field conditions and investigate P transformation across different soil types, including Oxisols and Vertisols, using complementary analytical techniques.

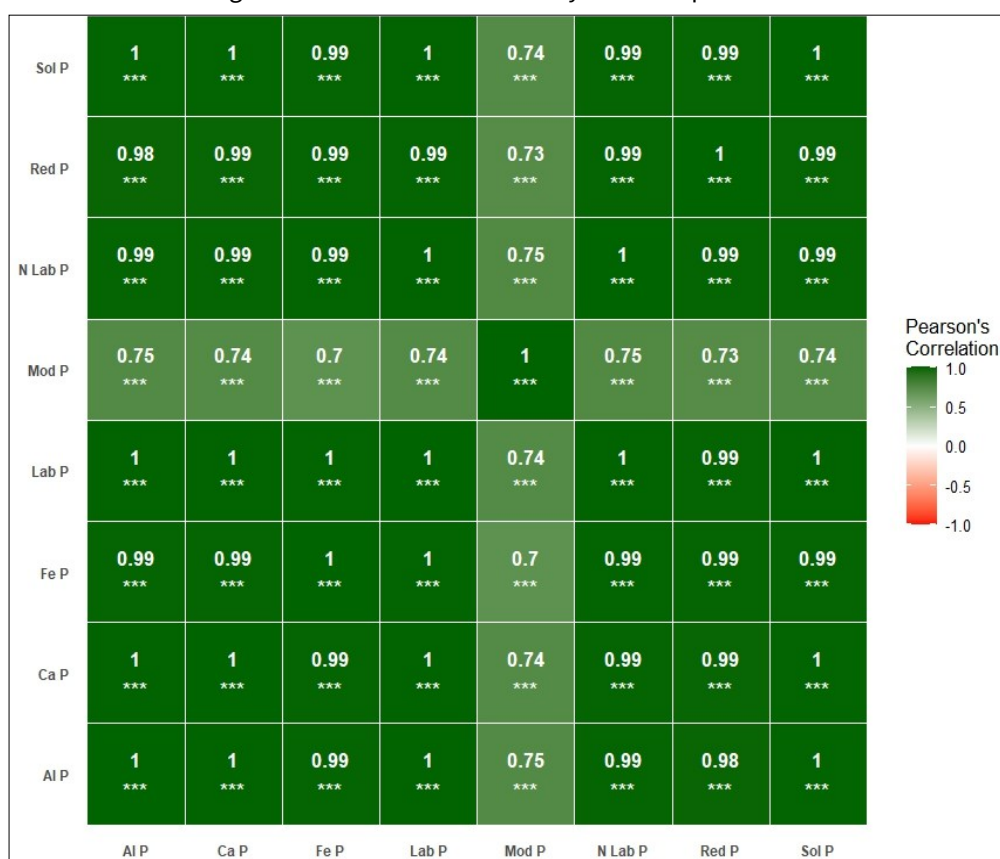


Fig. 3. Pearson's correlation matrix showing the relationship among phosphorus fractions, indicating strong positive correlations among stable phosphorus pools and moderate association of moderately labile phosphorus.

Conclusion

Based on the study results, the phosphorus (P) application rate and incubation period significantly influenced P transformation in the Inceptisol. Application of potassium dihydrogen phosphate (KH_2PO_4) increased P availability, as reflected by the higher concentrations of soluble P fractions, which reached their maximum levels on the 20th day of incubation. Subsequently, P was progressively transformed through fixation, adsorption and precipitation into less-available fractions, including iron-bound phosphorus (Fe-P), aluminium-bound phosphorus (Al-P), calcium-bound phosphorus (Ca-P) and non-labile P. These findings demonstrate the strong P-fixing capacity of the studied Inceptisol and highlight the practical need for split or slow-release P fertilisation strategies, timed according to crop demand, to sustain plant-available P and improve fertiliser-use efficiency. Future research should validate these findings under field conditions across different soil types and cropping systems and evaluate integrated P management practices, including the use of organic amendments and phosphate-solubilising microorganisms, to enhance P availability and fertiliser-use efficiency.

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Authors' contributions

VS conducted the experiments, collected and analysed the data and prepared the initial manuscript draft. RAS conceptualised and supervised the study, designed the treatment protocols, guided the experimental work, reviewed the observations and analyses and critically revised the manuscript. KA and RN verified the experimental results, validated the data analysis, reviewed the findings and approved the final version of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used TURNITIN in order to PARAPHRASE. After using this tool or service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

References

- Bowman RA. A sequential extraction procedure with concentrated sulfuric acid and dilute base for soil organic phosphorus. *Soil Sci Soc Am J.* 1989;53(2):362–6. <https://doi.org/10.2136/sssaj1989.03615995005300020008x>
- Cross AF, Schlesinger WH. A literature review and evaluation of the Hedley fractionation: applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma.* 1995;64(3–4):197–214. [https://doi.org/10.1016/0016-7061\(94\)00023-4](https://doi.org/10.1016/0016-7061(94)00023-4)
- da Silva LJ, da Silva AP, da Silva AC, Antonangelo JA, Bonetti JA, Fernandes DM, et al. Soil chemical properties effect on phosphorus fractions and maximum adsorption capacity in Brazilian tropical soils. *Soil Sci Soc Am J.* 2026;90(2):e70223. <https://doi.org/10.1002/saj2.70223>
- Kittrick JA. The free energy of formation of gibbsite and $\text{Al}(\text{OH})_4$ -from solubility measurements. *Soil Sci Soc Am J.* 1966;30(5):595–8. <https://doi.org/10.2136/sssaj1966.03615995003000050018x>
- Kumar S, Srivastava A, Gupta A. Effect of organic amendments on availability of different chemical fractions of phosphorus. *Agric Sci Dig.* 2015;35(2):83–8. <https://doi.org/10.5958/0976-0547.2015.00033.6>
- Rawajfih Z, Khresat S, Ryan J. Soil phosphorus fractions in calcareous Vertisols and Aridisols of northern Jordan. *Jordan J Agric Sci.* 2010;6(3):411.
- Jackson ML. Free oxides, hydroxides and amorphous aluminosilicates. In: *Methods of soil analysis: part 1 physical and mineralogical properties, including statistics of measurement and sampling.* 1965;9:578–603. <https://doi.org/10.2134/agronmonogr9.1.c45>
- Oades JM. Soil organic matter and structural stability: mechanisms and implications for management. *Plant Soil.* 1984;76(1):319–37. <https://doi.org/10.1007/BF02205590>
- Syers JK, Williams JD, Walker TW. The determination of total phosphorus in soils and parent materials. *N Z J Agric Res.* 1968;11(4):757–62. <https://doi.org/10.1080/00288233.1968.10422453>
- Yi C, Zhu J, Chen L, Huang X, Wu R, Zhang H, et al. Speciation of iron and aluminum in relation to phosphorus sorption and supply characteristics of soil aggregates in subtropical forests. *Forests.* 2023;14(9):1804. <https://doi.org/10.3390/f14091804>
- Lemos JD, Freire FJ, Souza VS, Oliveira EC, Lucena PG, Silva SR, et al. Phosphorus fractions in soils with distinct mineralogy and their relationship with phosphate buffer capacity indicators in Brazil. *Acta Sci Agron.* 2022;44:e55148. <https://doi.org/10.4025/actasciagron.v44i1.55148>
- Murphy JA, Riley JP. A modified single solution method for the determination of phosphate in natural waters. *Anal Chim Acta.* 1962;27:31–6. [https://doi.org/10.1016/S0003-2670\(00\)88444-5](https://doi.org/10.1016/S0003-2670(00)88444-5)
- Saha BN, Saha S, Poddar P, Chand T. Phosphate fractions as influenced by long-term phosphorus fertilization. *Indian J Agric Res.* 2013;47(1).
- Wang Q, Zhang N, Chen Y, Qin Z, Jin Y, Zhu P, et al. The phosphorus availability in Mollisol is determined by inorganic phosphorus fraction under long-term different phosphorus fertilization regimes. *Agronomy.* 2022;12(10):2364. <https://doi.org/10.3390/agronomy12102364>
- Olsen SR. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *US Department of Agriculture;* 1954.
- Chang SC, Jackson ML. Fractionation of soil phosphorus. *Soil Sci.* 1957;84(2):133–44. <https://doi.org/10.1097/00010694-195708000-00005>
- Milić S, Ninkov J, Vasin J, Zeremski T, Jakšić S, Živanov M, et al. Organic phosphorus fractions in relation to soil aggregate fractions of black soil. *Agronomy.* 2024;14(5):1022. <https://doi.org/10.3390/agronomy14051022>
- Nunes RD, de Sousa DM, Goedert WJ, de Oliveira LE, Pavinato PS, Pinheiro TD. Distribution of soil phosphorus fractions as a function of long-term soil tillage and phosphate fertilization management. *Front Earth Sci.* 2020;8:350. <https://doi.org/10.3389/feart.2020.00350>
- Watanabe FS, Olsen SR. Test of an ascorbic acid method for determining phosphorus in water and NaHCO_3 extracts from soil. *Soil Sci Soc Am J.* 1965;29(6):677–8. <https://doi.org/10.2136/sssaj1965.03615995002900060025x>
- Richardson AE, Simpson RJ. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. *Plant Physiol.* 2011;156(3):989–96. <https://doi.org/10.1104/pp.111.175448>

21. Hedley MJ, Stewart JW, Chauhan BS. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Sci Soc Am J.* 1982;46(5):970–6. <https://doi.org/10.2136/sssaj1982.03615995004600050017x>
22. Prasad R, Shivay YS. Phosphorus× other plant nutrient interactions, reaction products, anion exchange and phosphate fixation in soil and strategies to increase availability of the native and applied P to crop plants: a mini review and critique. *Agric Rev.* 2021;42(2). <https://doi.org/10.18805/ag.R-2028>
23. Warncke DD, Barber SA. Diffusion of zinc in soil: II. The influence of soil bulk density and its interaction with soil moisture. *Soil Sci Soc Am J.* 1972;36(1):42–6. <https://doi.org/10.2136/sssaj1972.03615995003600010009x>
24. Tiecher T, Gatiboni L, Lima AP, Filippi D. Accumulation of phosphorus fractions in contrasting soils under long-term phosphate fertilization. *J Environ Qual.* 2026. <https://doi.org/10.1002/jeq2.70120>

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