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Transformation of Phosphorus Fractions in Various Soil Types of Kerala: An Incubation Study

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Authors' contributions

This work was carried out in collaboration among all authors. Author AGJ managed the analyses of the study, performed statistical analysis and wrote the first draft of the manuscript. Author RMR designed the study. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Research study was undertaken to examine the dynamic changes and transformations of applied phosphorus (P) in soil, spanning a comprehensive period of 75 days, to understand its interactions and potential impact on nutrient availability.
Study Design: Factorial CRD.
Place and Duration of Study: Department of Soil Science and Agricultural Chemistry, Vellanikkara, Thrissur, between September 2023 and December 2023.

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Methodology: Soil samples collected from three different agroecological units (AEU) of Kerala varying in physicochemical properties were selected for the study Plastic containers filled with 300g of processed soil were treated with four levels of phosphorus as KH_2PO_4, with three replications for each treatment. The experiment was laid under factorial completely randomized design (CRD). On 15th, 45th and 75th day, each treatment combinations were analysed for pH, Electrical conductivity (EC), Available P (Av. P) and different fractions of phosphorus viz. Saloid-bound P (SB-P), Aluminum phosphate (Al-P), Iron phosphate (Fe-P), Reductant soluble phosphate (RS-P), Calcium phosphate (Ca-P) and Organic P (OP).

Results: Soil types had significant influence on pH, electrical conductivity, available phosphorus and various phosphorus fractions. The levels of phosphorus had significant influence on pH, EC, Av. P and phosphorus fractions except RS-P. Incubation period had significant effect on EC, Av. P and all phosphorus fractions but did not influence pH. The interaction among soil type, phosphorus levels and incubation period did not have significant influence on pH, available P and RS-P. Formation of Fe-P and Al-P was found highest on 15th day.

Conclusion: EC, SB-P, OP was found to be highest on 75th day of incubation due to the slow dissolution, desorption as well as immobilisation and mineralisation reactions in the soil. The rapid precipitation of available phosphorus as Fe and Al phosphates reduces the likelihood of RS-P formation. Due to slow diffusion of P into sesquioxide, the highest value of RS-P was recorded on 75th day of incubation. It was also notable that RS-P was not influenced by the level of P. Ca-P formation was found lowest in *Kuttanad* soil due to ultra-acidic condition.

Keywords: Incubation; soil types; phosphorus fractions; transformation.

1. INTRODUCTION

Phosphorus is a crucial macronutrient required by plants for various physiological processes. However, its availability can be limited due to several factors. Only a small fraction of total soil phosphorus is readily available for plant uptake. This fraction exists in the soil solution as inorganic phosphate ions (such as $H_2PO_4^-$ and HPO_4^{2-}). The majority of phosphorus is retained by various components, making it less accessible to plants [1].

Soil phosphorus exists in two forms: the Organic P, constitutes approximately 29% to 65% of total soil phosphorus, while the remaining 35% to 71% is in inorganic forms either as labile or occluded forms of P [2]. Organic phosphorus consists of decomposed plant/ animal matter and soil microbes. In acidic soils, labile P is adsorbed onto the surfaces of Fe and Al oxides, clay minerals, leading to the formation of Fe and Al-P minerals. Conversely, in neutral and calcareous soils, the destiny of P is regulated by its adsorption onto the surfaces of calcium carbonate ($CaCO_3$) and clay minerals and/or its precipitation as calcium phosphate (Ca-P) minerals [3].

Phosphorus transformation in the soil is regulated by chemical reactions which cause its retention or release. Adsorption and precipitation reactions are key mechanisms in phosphorus retention. Non-specific adsorption occurs on variable charged minerals, particularly Fe and Al oxides, hydroxides, and 1:1 minerals such as kaolinite. Phosphorus retention in soil is enhanced when positive net surface charge development and an increase in electric potential occurs as pH drops below the PZC of the minerals [4]. In specific adsorption, the replacement of protonated hydroxyl groups of central Fe or Al atom by phosphate ions results in forming inner-sphere complexes, in which phosphate ions are adsorbed either through monodendate or bidendate forms [5].

Sequential fractionation is the most used procedure to understand the dynamics of inorganic P in the soil. There are several fractionation schemes widely used to characterize soil P availability. The sequential extraction method developed by Chang and Jackson [6] is widely used to analyze various inorganic phosphorus pools. It is commonly employed to study the transformations of applied phosphate [7-10] and native phosphate forms [11,12] viz. saloid bound P (SB-P), aluminum phosphate (Al-P), iron phosphate (Fe-P), reductant soluble phosphate (RS-P) and calcium phosphate (Ca-P). The extraction procedure developed by Hedley et al. [13] fractionates soil phosphorus into five inorganic (Pi) pools, three organic (Po) pools and one residual pool. The procedure extracts the easily available P from soil initially with mild extractants followed by more stable P forms with stronger extractants. The extractants and corresponding forms of phosphorus include: anion exchange resin (Pi), $NaHCO_3$ (Pi and Po), NaOH (Pi and Po), NaOH with sonication (Pi and Po), HCl (Pi)and concentrated H_2SO_4 digestion (residual P) [14].

In highly weathered soils, inorganic P fractions are composed of chemically more stable and relatively insoluble forms [15]. Sharma et al. [16] reported that in acidic soils majority of the added P was transformed into Al-P which increased up to 7 days and then slowly decreased over the next 90 days at all application levels. They also found that very little phosphorus was converted to calcium-bound phosphorus (Ca-P). Additionally, organic phosphorus tended to increase in acidic soils [17]. Kothandaraman and Krishnamoorthy [18] revealed that in the laterite soils of Tamil Nadu, total phosphorus, inorganic phosphorus and phosphorus fractions such as Al-P, Fe-P, RS-P and occluded P were predominant. Conversely, Ca-P predominated in black and alluvial soils.

The research study sought to uncover the transformation of phosphorus into various chemical forms, ultimately providing insights into optimizing fertilization practices for enhanced crop yield and environmental sustainability.

2. MATERIALS AND METHODS

2.1 Soil Collection and Analysis

Surface soil samples with wide variations in the pH, texture and organic carbon content were collected from three agroecological units of Kerala viz. Northern coastal plain (AEU-2), *Kuttanad* (AEU-4) and North central laterite (AEU-10) having geographic coordinates N 10º 35' 28.961", E 76º 0' 5.929", N 9º 22' 33.352", E 76º 22' 51.729" and N 10º 48' 42.919", E 76º 11' 27.736" respectively. The samples were processed and analysed for various physico-chemical parameters namely pH, electrical conductivity (EC), organic carbon (OC), texture, cation exchange capacity (CEC), anion exchange capacity (AEC), available and total P and available Fe. Also, CBD extractable and oxalate extractable P, Fe and Al were estimated. The phosphorus fixation capacity was assessed using the method described by Waugh and Fitts [19], which involves the determination of available phosphorus (P) after incubating soil samples with different phosphorus concentrations for 96 hours and DPS was derived from oxalate extractable P, Fe and Al [20]. All the analyses were conducted in triplicate.

The incubation study was conducted to understand the transformation of added P over time in different soil types. It was laid out in factorial completely randomized design (CRD) with three factors viz. soil types, levels of phosphorus and period of incubation. The soil types include samples from the Northern coastal plain, North central laterite and *Kuttanad* denoted as S_1, S_2 and S_3. The levels of P constitute T_0- 0 mg kg^{-1}, T_1-10 mg kg^{-1}, T_2- 50 mg kg^{-1} and T_3-100 mg kg^{-1}. The samples were analysed on the 15^{th}, 45^{th} and 75^{th} day of incubation. Plastic containers of uniform size were filled with 300 g of processed soil samples and 4 levels of P were added as KH_2PO_4. Three replications of each treatment were maintained and were kept at field capacity by adding distilled water. On the 15^{th}, 45^{th} and 75^{th} day of incubation, each treatment combinations were analysed for pH, EC, available P and different fractions of phosphorus viz. saloid-bound P (SB-P), aluminum phosphate (Al-P), iron phosphate (Fe-P), reductant soluble phosphate (RS-P), calcium phosphate (Ca-P) and organic P (OP).

2.2 Soil P Fractions Analysis

Phosphorus fractions were determined using the Peterson and Corey [11] fractionation scheme. Soil sample of 1g was taken for the fractionation analysis. It was initially extracted with 50 mL of 1N NH_4Cl, after 30 minutes of shaking (easily soluble and loosely bound, referred to as SB-P). The residual soil was again shaken with 50 mL of 0.5N NH_4F (pH 8.2) for 1 hour (Al-P). The remaining soil underwent two washes with 25 mL of saturated NaCl. Subsequently, 50 mL of 0.1N NaOH was added and the mixture was shaken for 17 hours (Fe-P). The residue underwent two washes with saturated NaCl. Following this, it was suspended in 40 mL of 0.3M tri-sodium citrate, 5 mL of 1M $NaHCO_3$ and 1 g of solid $Na_2S_2O_4$. The mixture was shaken for 5 minutes and then heated in a water bath at 75°C to 80°C. After another 5 minutes of shaking, the suspension was centrifuged (RS-P). The residue was washed with saturated NaCl. Subsequently, 50 mL of 0.5N H_2SO_4 was introduced and shaken for 1 hour, to extract Ca-P. Finally, for the estimation of organic P, samples were ignited at 550°C for one hour. After cooling, the samples were transferred to centrifuge tubes. A duplicate set of soil was taken. In both sets, 50 mL of 0.2N H_2SO_4 was added and shaken for 16 hours and 30 minutes. Organic P fractions were measured by the difference of total P and the inorganic P. All P fractions were determined by ICP-OES (model: Perkin Elmer-Optima 8000).

2.3 ANOVA

Statistical analysis of the incubation experiment was done using the GRAPES statistical software of Kerala Agricultural University.

3. RESULTS AND DISCUSSION

Physicochemical properties of three AEUs of Kerala which are included in the study are represented in Table 1.

3.1 Effect of Soil Type, Levels of Phosphorus and Incubation Time on Soil pH

Soil type significantly influenced its pH in which laterite exhibited the highest mean value of 6.32 and the lowest mean value of 2.57 observed in *Kuttanad* (Table 2). This discrepancy in pH can be attributed to their initial pH conditions. Similarly, in *Kuttanad*, the untreated treatment combination outperformed all treated combinations likely attributable to the inherent buffering capacity, enhanced by high organic matter content.

Although the individual effect of the incubation period showed no significant impact on pH, the interaction between soil type and incubation period displayed a notable influence, likely driven by the dominant effect of soil type. In sandy soils, all incubation periods led to significant pH changes, reflecting the low buffering capacity of this soil type. Conversely, *Kuttanad* maintained consistent pH levels across all incubation periods, indicative of its high buffering power. The stabilization of pH could be attributed to the combined effects of soil buffer capacity and the buffering action of KH_2PO_4, resulting in no significant interaction effect between soil type, P levels and incubation period.

Table 1. Physico-chemical properties of experimental soils

Particulars	Northern coastal plain	North central laterite	*Kuttanad*	Methods
pH (1: 2.5:: Soil: Water)	6.01	6.49	3	Jackson [21]
Electrical conductivity, dS m^{-1}	0.03	0.16	4.41	Jackson [21]
Sand (%)	83.34	77.93	34.73	Piper [22]
Silt (%)	9.44	7.02	32.18	
Clay (%)	7.22	15.05	33.10	
Texture	Loamy sand	Sandy loam	Clay loam	
Organic carbon, %	0.42	1.71	4.77	Walkley and Black [23]
CEC, cmol (+) kg^{-1}	2.17	10.61	19.45	Hendershot and Duquette [24]
AEC, cmol (-) kg^{-1}	6.51	14.95	33.00	Hesse [25]
Available P, kg ha^{-1}	160.04	15.17	2.41	Watanabe and Olsen [26]
Total P, mg kg^{-1}	1094	1248	882	Koening and Johnson [27]
Av. Fe, mg kg^{-1}	20.88	168	408.13	Sims and Johnson [28]
Fe_{CBD}, mmolkg^{-1}	24.92	286.24	102.69	Mehra and Jackson [29]
Al_{CBD}, mmolkg^{-1}	1.64	37.02	18.97	
P_{CBD}, mmolkg^{-1}	9.48	13.04	8.51	
Fe_{OX}, mmolkg^{-1}	66.21	74.47	83.94	Mckeaguue and Day [30]
Al_{OX}, mmolkg^{-1}	27.43	54.87	44.74	
P_{OX}, mmolkg^{-1}	15.16	15.87	7.98	
PFC, %	45	85.5	85.12	Waugh and Fitts [19]
DPS, %	32.38	24.54	12.40	Beauchemin and Simard [20]

Table 2. Effect of soil type and days of incubation on pH

Soil Type	Days of incubation			Mean
	15 (D_1)	**45 (D_2)**	**75 (D_3)**	
Northern coastal plain (S_1)	5.74	5.59	5.46	**5.59**
North central laterite (S_2)	6.21	6.43	6.33	**6.32**
***Kuttanad* (S_3)**	2.61	2.55	2.56	**2.57**
Mean	**4.85**	**4.86**	**4.78**	**4.83**
CD (0.05): S X D	**0.12**			
CD (0.05): S	**0.07**			
CD (0.05): T	**0.08**			
CD (0.05): D	**NS**			

Table 3. Effect of soil type and days of incubation on EC

Soil Type	Days of incubation			Mean
	15 (D_1)	**45 (D_2)**	**75 (D_3)**	
Northern coastal plain (S_1)	0.17	0.20	0.25	**0.21**
North central laterite (S_2)	0.15	0.16	0.68	**0.33**
***Kuttanad* (S_3)**	5.54	6.37	10.47	**7.46**
Mean	**1.95**	**2.24**	**3.80**	**2.67**
CD (0.05): S X D	**0.22**			
CD (0.05): S	**0.13**			
CD (0.05): D	**0.13**			

Table 4. Effect of soil type, levels of phosphorus and days of incubation on EC

Days of incubation	Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
		0 (T_0)	**10 (T_1)**	**50 (T_2)**	**100 (T_3)**	
15 (D_1)	Northern coastal plain (S_1)	0.11	0.17	0.21	0.20	**0.17**
	North central laterite (S_2)	0.14	0.14	0.15	0.16	**0.15**
	Kuttanad (S_3)	3.59	5.96	6.24	6.37	**5.54**
Mean		**1.28**	**2.09**	**2.20**	**2.25**	**1.95**
45 (D_2)	Northern coastal plain (S_1)	0.12	0.22	0.24	0.20	**0.20**
	North central laterite (S_2)	0.15	0.16	0.16	0.16	**0.16**
	Kuttanad (S_3)	3.79	6.69	7.67	7.34	**6.37**
Mean		**1.35**	**2.36**	**2.69**	**2.50**	**2.24**
75 (D_3)	Northern coastal plain (S_1)	0.16	0.29	0.22	0.33	**0.25**
	North central laterite (S_2)	0.72	0.67	0.66	0.68	**0.68**
	Kuttanad (S_3)	6.95	6.02	14.43	14.49	**10.47**
Mean		**2.61**	**2.33**	**5.10**	**5.17**	**3.80**
CD (0.05) S X T X D:	**0.44**					
CD (0.05): S	**0.13**					
CD (0.05): T	**0.14**					
CD (0.05): D	**0.13**					

3.2 Effect of Soil Type, Levels of Phosphorus and Incubation Time on Electrical Conductivity (EC)

Soil type wielded a significant influence on electrical conductivity (EC), with *Kuttanad* having the highest mean value of 7.46 dS m^{-1} (Table 3), potentially attributed to the influence of seawater. Mean EC values of the Northern coastal plain and laterite were on par. The effects of soil type, various phosphorus doses and incubation periods on EC are depicted in Table 4. Treatments T_2 and T_3 showcased superior or comparable EC values, while T_0 recorded the lowest EC, illustrating an increase in soluble salts with escalating KH_2PO_4 concentration. Geetha [31] and Eresh [32] corroborated this trend, noting a rise in EC upon fertilizer addition due to steady salt dissolution. The incubation period significantly influenced EC, with a noticeable uptick as days progressed, likely attributable to dynamic equilibrium due to desorption, solubilization and mineralization.

On the 15th, 45th and 75th day of incubation, Northern coastal plain displayed consistent EC levels, whereas *Kuttanad* exhibited significant variation, indicative of pronounced ion release into the soil solution, potentially due to high cation exchange capacity of *Kuttanad* compared to Northern coastal plain. The synergistic influence of soil type, incubation duration and increased KH_2PO_4 concentration culminated in the highest EC value (14.49 dS m^{-1}) in $S_3T_3D_3$.

3.3 Effect of Soil Type, Levels of Phosphorus and Incubation Time on Available Phosphorus

Various factors including different levels of phosphorus, soil types and incubation periods significantly affected the available phosphorus. The highest mean value (66.38 mg kg^{-1}) of available phosphorus was observed in Northern coastal plain, followed by laterite (25.74 mg kg^{-1}) and *Kuttanad* (6.83 mg kg^{-1}) (Table 5). This discrepancy may be due to the inherent available phosphorus content of each soil, in which *Kuttanad* had the lowest available phosphorus levels potentially contributed by low pH, high organic carbon and sesquioxide contents.

The interaction between soil type and days of incubation, as well as the interaction among soil type, phosphorus levels and days of incubation, did not result in a significant effect on available phosphorus. However, the interaction between phosphorus levels and days of incubation proved significant, with the highest mean value of available phosphorus (33.96 mg kg^{-1}) observed on the 15th day of incubation, paralleled by values on the 75th day (Table 6). Treatment combination with the highest phosphorus levels on the 15th day of incubation recorded a superior value (55.27 mg kg^{-1}) of available phosphorus.

Table 5. Effect of soil type and levels of phosphorus on availability of P (mg kg^{-1})

Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
	0 (T_0)	**10 (T_1)**	**50 (T_2)**	**100 (T_3)**	
Northern coastal plain (S_1)	42.78	49.29	72.55	100.89	**66.38**
North central laterite (S_2)	13.77	17.93	29.74	41.53	**25.74**
***Kuttanad* (S_3)**	5.09	5.26	6.71	10.24	**6.83**
Mean	**20.55**	**24.16**	**36.33**	**50.89**	**32.9**
CD (0.05): S X T	**2.76**				
CD (0.05): S	**1.378**				
CD (0.05): T	**1.591**				

Table 6. Effect of levels of P and days of incubation on availability of P (mg kg^{-1})

Levels of P added (mg kg^{-1})	Days of incubation			Mean
	15 (D_1)	**45 (D_2)**	**75 (D_3)**	
0 (T_0)	19.41	19.65	22.59	**20.55**
10 (T_1)	23.95	23.25	25.38	**24.16**
50 (T_2)	37.21	35.98	35.81	**36.33**
100 (T_3)	55.27	48.42	48.97	**50.89**
Mean	**33.96**	**31.82**	**33.19**	**32.99**
CD (0.05): T X D	**2.76**			
CD (0.05): T	**1.59**			
CD (0.05): D	**1.38**			

3.4 Effect of Soil Type, Levels of Phosphorus and Incubation Time on Phosphorus Fractions

3.4.1 Saloid- bound phosphorus (SB-P)

There is a significant effect, encompassing both main and interaction effects, of soil type, phosphorus levels and incubation period on saloid-bound phosphorus (SB-P). In *Kuttanad*, elevated Fe_{CBD}, high organic carbon content, maximal clay content and minimal pH were noted, suggesting the likelihood of strong surfaces for binding of added phosphorus, resulting in a scant quantity of SB-P (3.17 mg kg^{-1}) (Table 7). Comparing 3 soils, Northern coastal plain had the highest value of SB-P. Similar findings were observed by Vijayan [33].

The main effect of incubation time on SB-P was significant, with the highest value of 21.20 mg kg^{-1} on the 75th day (Table 7), indicative of gradual dissolution, mineralization, or desorption of phosphorus as part of changes in dynamic equilibrium over time. All varying phosphorus levels elicited significantly different effects on SB-P only in Northern coastal plain, while treatment effects in *Kuttanad* were comparable (Table 8). A decrease in SB-P was observed on the 45th day in all soil types, possibly due to strong phosphorus binding after the immediate availability of added phosphorus. Followed by an increase on the 75th day, which may be due to a shift in dynamic equilibria. Upon comparing the interaction effect of the three factors, the highest SB-P of 38.28 mg kg^{-1} was observed in $S_1T_3D_3$. Varying phosphorus levels failed to produce a significant effect on SB-P in *Kuttanad*, particularly on the 45th and 75th day, underscoring its high phosphorus-fixing nature and the availability of high-affinity surfaces in this soil.

3.4.2 Aluminum phosphate (Al-P)

Soil type, phosphorus levels and incubation period exerted significant influence on aluminum phosphate. Among soil types, Northern coastal plain exhibited the highest mean aluminum phosphate content (100.31 mg kg^{-1}), followed by laterite (84.12 mg kg^{-1}) and *Kuttanad* (61.46 mg kg^{-1}). This variability primarily stems from prevailing pH conditions in these soils. Notably, *Kuttanad* exhibited a mean pH value of 2.57 (Table 9). Wang et al. [34] demonstrated that AAH (amorphous aluminum hydroxide) possesses an exceptionally high phosphate sorption capacity, intensifying from 3.80 mmol/g at pH 7 to 4.63 mmol/g at pH 3. Furthermore, they observed a direct and consistent increase in the percentage of phosphate precipitating as amorphous aluminum phosphate (AAP) correlating with phosphate sorption. Different phosphorus levels significantly affected aluminum phosphate, with the highest value observed for T_3, indicating the potential for phosphorus precipitation as aluminum phosphate when sufficient aluminum ions are present, aligning with the aforementioned findings.

The highest mean aluminum phosphate value (230.49 mg kg^{-1}) recorded for $S_1T_3D_1$ (Table 10) may be attributed to the positive interaction effect of favorable pH, higher phosphorus concentration and rapid precipitation due to fewer high-affinity colloidal surfaces. Higher aluminum phosphate levels were observed on the 15th day of incubation across all soil types, indicating rapid precipitation regardless of soil type.

Table 7. Effect of soil type and days of incubation on SB-P (mg kg^{-1})

Soil Type	Days of incubation			Mean
	15 (D_1)	45 (D_2)	75 (D_3)	
Northern coastal plain (S_1)	22.79	15.77	32.73	**23.76**
North central laterite (S_2)	22.19	12.93	25.37	**20.16**
***Kuttanad* (S_3)**	2.88	1.12	5.51	**3.17**
Mean	**15.96**	**9.94**	**21.20**	**15.70**
CD (0.05): S X D	**0.71**			
CD (0.05): S	**0.41**			
CD (0.05): D	**0.41**			

Table 8. Effect of soil type, levels of phosphorus and days of incubation on SB-P (mg kg^{-1})

Days of incubation	Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
		0 (T_0)	**10 (T_1)**	**50 (T_2)**	**100 (T_3)**	
15 (D_1)	Northern coastal plain (S_1)	15.61	16.64	22.58	36.35	**22.79**
	North central laterite (S_2)	18.54	18.14	22.16	29.92	**22.19**
	Kuttanad (S_3)	1.26	3.18	3.12	3.98	**2.88**
Mean		**11.80**	**12.65**	**15.95**	**23.42**	**15.96**
45 (D_2)	Northern coastal plain (S_1)	11.65	13.58	16.62	21.23	**15.77**
	North central laterite (S_2)	10.55	11.87	13.72	15.60	**12.93**
	Kuttanad (S_3)	0.94	1.18	1.20	1.17	**1.12**
Mean		**7.71**	**8.87**	**10.51**	**12.67**	**9.94**
75 (D_3)	Northern coastal plain (S_1)	29.25	30.12	33.27	38.28	**32.73**
	North central laterite (S_2)	18.10	19.13	30.17	34.07	**25.37**
	Kuttanad (S_3)	5.32	5.63	5.56	5.51	**5.51**
Mean		**17.56**	**18.29**	**23.00**	**25.95**	**21.20**
CD (0.05)	**1.43**					

Table 9. Effect of soil type and levels of phosphorus on Al-P (mg kg^{-1})

Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
	0 (T_0)	**10 (T_1)**	**50 (T_2)**	**100 (T_3)**	
Northern coastal plain (S_1)	74.70	84.40	99.55	142.58	**100.31**
North central laterite (S_2)	70.85	76.17	87.94	101.51	**84.12**
***Kuttanad* (S_3)**	59.91	57.44	58.72	69.79	**61.46**
Mean	**68.48**	**72.67**	**82.07**	**104.63**	**81.96**
CD (0.05): S X T	**3.98**				
CD (0.05): S	**1.99**				
CD (0.05): T	**2.30**				

Table 10. Effect of soil type, levels of phosphorus and days of incubation on Al-P (mg kg^{-1})

Days of incubation	Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
		0 (T_0)	**10 (T_1)**	**50 (T_2)**	**100 (T_3)**	
15 (D_1)	Northern coastal plain (S_1)	120.49	131.53	147.70	230.49	**157.55**
	North central laterite (S_2)	124.49	124.52	138.61	148.78	**134.10**
	Kuttanad (S_3)	109.88	110.28	110.94	120.30	**112.85**
Mean		**118.29**	**122.11**	**132.42**	**166.52**	**134.83**
45 (D_2)	Northern coastal plain (S_1)	41.45	51.37	65.87	88.83	**61.88**
	North central laterite (S_2)	36.80	47.60	58.42	61.22	**51.01**
	Kuttanad (S_3)	36.55	28.15	30.42	49.25	**36.09**
Mean		**38.27**	**42.37**	**51.57**	**66.44**	**49.66**
75 (D_3)	Northern coastal plain (S_1)	62.15	70.30	85.08	108.42	**81.49**
	North central laterite (S_2)	51.25	56.38	66.78	94.52	**67.23**
	Kuttanad (S_3)	33.30	33.88	34.78	39.83	**35.45**
Mean		**48.90**	**53.52**	**62.22**	**80.92**	**61.39**
CD (0.05)	**6.89**					

3.4.3 Iron phosphate (Fe-P)

The impact of soil types and varying phosphorus on iron phosphate levels in Northern coastal plain, laterite and *Kuttanad* is depicted in Table 11. We observed significant main and interaction effects of soil type, P levels and incubation periods on iron phosphate. Laterite exhibited the highest mean iron phosphate value (265.52 mg kg^{-1}), followed by *Kuttanad* and Northern coastal plain soil. A study by Lindsay and Ment [35] investigated the alteration of ferric phosphates due to liming, revealing that the ferric phosphate precipitate strengite becomes entirely unavailable in acidic soil limed to pH 7.6. Moreover, the presence of Fe content significantly influences the precipitation of iron phosphate. Northern coastal plain, characterized by reduced available Fe content, consequently displayed the least amount of Fe phosphate. Treatment T_3 demonstrated a significantly superior effect on Fe-P highlighting the influence of higher P concentration on iron phosphate precipitation. The interaction between soil type and P levels showcased a superior effect on Fe-P in S_2T_3, with a value of 295.75 mg kg^{-1}.

The main effect of incubation days suggests rapid iron phosphate precipitation, akin to aluminum phosphate, within 15 days of incubation (Table 12). Regarding the interaction between P levels and incubation days, all P levels produced a significant effect only on the 15^{th} day, with higher concentrations (T_3) demonstrating a significant effect on Fe-P.

3.4.4 Reductant soluble phosphate

Soil type had a significant influence on reductant soluble P. Laterite soil type had a superior and significant effect on RS-P with a mean value of 149.68 mg kg^{-1} (Table 13). On comparing the soils under study, the highest Fe_{CBD} and Al_{CBD} were recorded in laterite indicating the chances of reductant soluble phosphate in this soil. Varying levels of P couldn't produce a significant effect on RS-P. In the case of Fe-P and Al-P, the highest mean value was recorded on the 15^{th} day suggesting faster precipitation but a reverse trend was noted in RS-P. The highest mean value was recorded on the 75^{th} day whereas D_1(15^{th} day) and D_2 (45^{th} day) were on par (Table 14) indicating the occlusion of added P into iron and aluminum oxides are slow process. On considering the interaction effect of soil type and levels of P, all the treatments on laterite were superior to the treatments applied on other soils because of the dominance of iron and aluminum oxides. The interaction effect of soil type and days of incubation had significant influence on reductant soluble P. D_3 (75^{th} day) was found superior to D_1 and D_2 in all three-soil types (Table 14). The increase in reductant soluble P over time is very evident in the case of laterite. The faster transformation of added P into other forms might be the reason for the non-significant effect of the interaction of the soil type, levels of P and period of incubation.

3.4.5 Calcium phosphate (Ca-P)

Soil type had a significant effect on precipitation of calcium phosphate. The highest mean value of Ca-P is noted in Northern coastal plain. The lowest mean value of 30.09 mg kg^{-1} was observed in *Kuttanad* which might be due to the ultra-acidic condition in this soil (Table 15). In a study conducted by McDowell et al. [36] to understand the complex interactions between phosphorus (P) in different forms in the soil found that at pH above 5.8, soils are saturated with hydroxyapatite ($Ca_5(PO_4)_3OH$) and undersaturated with β-tricalcium phosphate ($\beta-Ca_3(PO_4)_2$). Varying levels of P had a significant influence on calcium phosphate content with the highest mean value of 68.57 mg kg^{-1} (Table 15) recorded for T_3 (100 mg kg^{-1}) but could not produce a significant influence on Ca-P in *Kuttanad* owing to the ultra-acidic condition of the soil, which is unfavorable for Ca-P formation.

It was found that incubation time had a significant effect on Ca-P when comparing the interaction effect of soil type, P levels and incubation days (Table 16) with the highest mean value on the 75^{th} day. Varying levels of P in *Kuttanad* soil did not produce a significant variation on the 15^{th}, 45^{th} and 75^{th} day of incubation, possibly due to unfavorable pH conditions for calcium phosphate precipitation.

Table 11. Effect of soil type and levels of phosphorus on Fe-P (mg kg^{-1})

Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
	0 (T_0)	10 (T_1)	50 (T_2)	100 (T_3)	
Northern coastal plain (S_1)	78.50	82.32	90.58	93.81	**86.30**
North central laterite (S_2)	257.23	247.15	261.96	295.75	**265.52**
***Kuttanad* (S_3)**	163.17	143.72	164.32	201.94	**168.29**
Mean	**166.30**	**157.73**	**172.28**	**197.17**	**173.37**
CD (0.05): S X T	**6.70**				
CD (0.05): S	**3.35**				
CD (0.05): T	**3.87**				

Table 12. Effect of soil type, levels of phosphorus and days of incubation on Fe-P (mg kg^{-1})

Levels of P added (mg kg^{-1})	Days of incubation			Mean
	15 (D_1)	45 (D_2)	75 (D_3)	
0 (T_0)	241.57	106.25	151.08	**166.30**
10 (T_1)	228.69	96.88	147.62	**157.73**
50 (T_2)	277.43	93.86	145.56	**172.28**
100 (T_3)	299.27	119.84	172.40	**197.17**
Mean	**261.74**	**104.21**	**154.17**	**155.04**
CD (0.05): T X D	**6.70**			
CD (0.05): T	**3.87**			
CD (0.05): D	**3.35**			

Table 13. Effect of soil type and levels of phosphorus on RS-P (mg kg^{-1})

Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
	0 (T_0)	10 (T_1)	50 (T_2)	100 (T_3)	
Northern coastal plain (S_1)	44.30	51.31	52.71	49.42	**49.44**
North central laterite (S_2)	150.16	160.96	148.36	139.23	**149.68**
***Kuttanad* (S_3)**	59.71	46.66	47.37	49.00	**50.69**
Mean	**84.72**	**86.31**	**82.81**	**79.21**	**83.27**
CD (0.05): S X T	**10.65**				
CD (0.05): S	**5.32**				
CD (0.05): T	**NS**				

Table 14. Effect of soil type and days of incubation on RS-P (mg kg^{-1})

Soil Type	Days of incubation			Mean
	15 (D_1)	45 (D_2)	75 (D_3)	
Northern coastal plain (S_1)	46.66	38.48	63.17	**49.44**
North central laterite (S_2)	131.48	146.07	171.47	**149.68**
***Kuttanad* (S_3)**	42.77	34.60	74.69	**50.69**
Mean	**73.64**	**73.05**	**103.11**	**83.27**
CD (0.05): S X D	**9.22**			
CD (0.05): S	**5.32**			
CD (0.05): D	**5.32**			

Table 15. Effect of soil type and levels of phosphorus on Ca-P (mg kg^{-1})

Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
	0 (T_0)	10 (T_1)	50 (T_2)	100 (T_3)	
Northern coastal plain (S_1)	106.87	108.45	93.74	118.42	**106.87**
North central laterite (S_2)	63.49	52.86	55.09	56.47	**56.97**
***Kuttanad* (S_3)**	30.45	28.68	30.42	30.81	**30.09**
Mean	**66.94**	**63.33**	**59.75**	**68.57**	**64.65**
CD (0.05): S X T	**7.61**				
CD (0.05): S	3.81				
CD (0.05): T	4.39				

3.4.6 Organic phosphate (OP)

Soil type had a significant effect on organic phosphate. The highest mean value of OP (272.15 mg kg^{-1}) was recorded in North central laterite and the lowest mean value was recorded in Northern coastal plain (75.14 mg kg^{-1}) (Table 17). The highest mean value in the laterite can be attributed to its highest total phosphorus content (1248 mg kg^{-1}) (Table 1). Days of incubation also had a significant effect on organic phosphate formation with the highest mean value recorded on the 75th day after a decrease in OP content on the 45th day.

On comparing the interaction effect of soil type, levels of P and incubation time, days of incubation also had a significant impact on organic phosphate formation with the highest mean value recorded on the 75th day after a decrease in OP content on the 45th day (Table 18) which might be due to the mineralization and immobilization of P content in the soil. Varying levels of P couldn't produce significant changes in *Kuttanad*, especially on the 15th and 45th day. It also indicates a slow transformation of added P to organic phosphate.

Table 16. Effect of soil type, levels of phosphorus and days of incubation on Ca-P (mg kg^{-1})

Days of incubation	Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
		0 (T_0)	10 (T_1)	50 (T_2)	100 (T_3)	
15 (D_1)	Northern coastal plain (S_1)	98.70	109.47	104.29	161.14	**118.40**
	North central laterite (S_2)	63.33	34.53	46.08	39.72	**45.91**
	Kuttanad (S_3)	18.59	16.30	20.70	16.29	**17.97**
Mean		**60.21**	**53.43**	**57.02**	**72.38**	**60.76**
45 (D_2)	Northern coastal plain (S_1)	101.60	101.48	77.02	57.57	**84.42**
	North central laterite (S_2)	70.90	63.72	63.17	65.37	**65.79**
	Kuttanad (S_3)	38.35	38.25	37.18	40.97	**38.69**
Mean		**70.28**	**67.82**	**59.12**	**54.64**	**62.96**
75 (D_3)	Northern coastal plain (S_1)	120.30	114.40	99.90	136.55	**117.79**
	North central laterite (S_2)	56.25	60.32	56.03	64.32	**52.49**
	Kuttanad (S_3)	34.40	31.50	33.38	35.18	**33.62**
Mean		**70.32**	**59.76**	**63.10**	**78.68**	**67.97**
CD (0.05)	**13.184**					

Table 17. Effect of soil type and levels of phosphorus on OP (mg kg^{-1})

Soil Type	Levels of phosphorus added (mg kg^{-1})				Mean
	0 (T_0)	10 (T_1)	50 (T_2)	100 (T_3)	
Northern coastal plain (S_1)	91.30	79.94	40.37	88.93	**75.14**
North central laterite (S_2)	292.09	288.91	255.25	252.35	**272.15**
***Kuttanad* (S_3)**	81.99	74.03	75.99	88.21	**80.06**
Mean	**155.13**	**147.63**	**123.87**	**143.87**	**142.45**
CD (0.05): S X T	**9.83**				
CD (0.05): S	**4.91**				
CD (0.05): T	**5.67**				

Table 18. Effect of soil type, levels of phosphorus and days of incubation on OP (mg kg^{-1})

Days of incubation	Soil Type	Levels of phosphorus (mg kg^{-1})				Mean
		0 (T_0)	10 (T_1)	50 (T_2)	100 (T_3)	
15 (D_1)	Northern coastal plain (S_1)	80.00	125.60	35.25	94.87	**83.93**
	North central laterite (S_2)	238.42	240.95	279.47	232.37	**247.83**
	Kuttanad (S_3)	73.70	71.17	74.28	68.12	**71.82**
Mean		**130.71**	**145.91**	**129.67**	**131.79**	**134.52**
45 (D_2)	Northern coastal plain (S_1)	92.92	10.99	2.50	86.87	**48.32**
	North central laterite (S_2)	115.35	199.23	109.32	167.77	**147.92**
	Kuttanad (S_3)	36.37	40.67	42.75	50.75	**42.64**
Mean		**81.55**	**83.63**	**51.52**	**101.80**	**79.63**
75 (D_3)	Northern coastal plain (S_1)	101.00	103.25	83.37	85.07	**93.17**
	North central laterite (S_2)	522.50	426.55	376.95	356.92	**420.73**
	Kuttanad (S_3)	135.90	110.25	110.95	145.78	**125.72**
Mean		**253.13**	**213.35**	**190.42**	**195.93**	**213.21**
CD (0.05)	**17.03**					

4. CONCLUSION

pH, electrical conductivity (EC), available phosphorus (Av. P) and various phosphorus fractions. The levels of phosphorus exhibited notable impacts on pH, EC and Av. P and all phosphorus fractions except reductant-soluble phosphate. The period of incubation did not yield a significant effect on pH. The interaction among soil type, phosphorus levels and days of incubation showed insignificance concerning pH, available P and reductant-soluble phosphorus. The reduction in saloid-bound P within 45 days of incubation can be attributed to the presence of strong affinity sites on the adsorbent surface resulting in the high phosphorus retention capacity of the soils. Notably, rapid precipitation of iron and aluminum phosphate occurred by the 15th day of incubation compared to the 45th and 75th day, suggesting a swift transformation of phosphate ions into insoluble precipitates, facilitated by the abundance of Fe, Al and phosphate ions in the soil. Conversely, reductant-soluble phosphate exhibited its highest values on the 75th day of incubation. The occlusion of phosphorus to Fe and Al oxides proceeded more slowly compared to the precipitation of Fe and Al phosphates in these soils, resulting in the formation of other phosphorus fractions. The formation of Ca-P was least pronounced in *Kuttanad* due to their ultra-acidic properties.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of manuscripts.

Details of the AI usage are given below:

1.ChatGPT (version: based on GPT-4 architecture; model: GPT-4; source: OpenAI)

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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