Research Article

Changes in Soil Phosphorus Pools and Chemical Properties under Liming in Nitisols of Farawocha, South Ethiopia

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Understanding the nutrient dynamics in acid soil is fundamental to carry out proper management. The study was conducted to investigate phosphorus (P) pools and selected properties under different rates of lime for acid nitisols of Farawocha, Southern Ethiopia. Four lime rates incubated for a month in three replications were tested. The lime rates were 0 t/ha (0%), 5.25 t/ha (50%), 10.5 t/ha (100%), and 15.75 t/ha (150%). Lime requirement (LR) for 100% was calculated targeting soil pH of 6.5. Data on the P pools such as soluble P (P-sol) and bounded forms of P with iron (Fe-P), aluminum (Al-P), calcium (Ca-P), organic part (Org-P), residual P (Res-P), and total of P fractions were measured. In addition, changes in soil chemical properties such as pH, exchangeable acidity, calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), copper (Cu), boron (B), zinc (Zn), and manganese (Mn) were analyzed. The result showed that total P was 357.5 mg/kg. Compared to nontreated soil, liming at a rate of 15.75 t/ha significantly improved P-sol (34.2%, $r^2 = 0.88$), Ca-P (61.6%, $r^2 = 0.92$), and Res-P (195%, $r^2 = 0.94$); however, it reduced Fe-P (58.5%, $r^2 = -0.83$), Al-P (71%, $r^2 = -0.97$), and Org-P (19.1%, $r^2 = 0.93$). Overall, the P-associated fractions in the soil, regardless of the lime rates, were in the order of Org_P > Res_P > Fe_P > Ca_P > Al_P > P-sol. Liming raised soil pH by 2.1 units (4.5 to 6.6) over nonlimed soil, whereas it reduced exchangeable acidity from 4.18 to 0.23 meq/100 g soil. Available P, Ca, Mg, S, Cu, Zn, and B contents were significantly improved with lime application. However, liming reduced Fe and Mn contents. In conclusion, these findings showed that liming facilitated the release of P from various pools, modified pH and exchangeable acidity, and resulted in beneficial changes for most of the soil chemical properties.

1. Introduction

Nitisols are deep, well-drained, red, tropical soils with diffuse horizon boundaries and a clay-rich "nitic" subsurface horizon that has typical "nutty," polyhedric, blocky structure elements with shiny ped faces, predominantly derived from basic parent rocks by strong weathering, but they are far more fertile than most other red tropical soils [1]. More than half of all the nitisols of tropical Africa are found in the Ethiopian highlands followed by Kenya, Congo, and Cameroon, among the most productive agricultural soils along with Vertisols, Luvisols, and Planosols [2]. Due to strong weathering and oxides of Fe and Al domination, nitisols usually have limited availability of phosphorus through fixation or retention [3, 4].

Phosphorus is the most yield-limiting plant nutrient in many regions of the world [5, 6], tropical Africa [7], and most Ethiopian soils [8, 9]. The forms of P greatly influence its availability in the soil and subsequently influence productivity [10]. In many soils, P availability is heavily restricted by binding to Fe and Al [7, 10, 11]. Even if the total soil P exceeds plant requirements, it is mostly in nonavailable forms for crop uptake [12] and locked in primary minerals, precipitated, adsorbed, or inorganically complexed forms, and only approximately 6% (range of 1.5%–11%) readily available to plants [13]. Inorganic P mostly consists of poorly soluble Ca phosphates and Fe and Al phosphates, respectively, in alkaline soils and acid soils [14]. Soil P chemistry is complex and P possibly transformed depending

on the environment [15]; therefore accurate assessment of P availability in soils and precise prediction of P fertilizer requirements are increasingly important for sustainable agriculture [16]. Due to this, the investigation of P fractions is important for the evaluation of its status and the chemical reactions in soil that influence soil fertility.

It was hypothesized that acidity and ensuing effects resulted in poor growth and that liming can correct these shortcomings. Due to this, the investigation of P fractions is important for the evaluation of its status and the chemical reactions in soil that influence soil fertility. Accordingly, this study evaluated the effects of lime on the dynamics of P fraction and the variation of some important soil chemical properties.

2. Materials and Methods

2.1. Description of the Study Area.
The study was conducted on the Wolaita Sodo University research farm which has been established to develop site-specific technologies. The farm is located in Wolaita Zones of Southern Ethiopia. The farm, for many years, was owned and managed using traditional practices but the productivity was low; soil acidity and inadequate fertilizer application were among many factors causing low productivity. In the field, it was also noted that plant growth was extremely retarded. Prior soil test results of research farms soils had shown strongly acidic reaction with a pH value of 4.5. The study site called Farawocha, a 3.85 ha farmland, lies between $07°6'34.33''$–$07°9'0.23''$N and $037°34'54.29''$- $037°37'33.43''$E located 55 km west of Sodo, capital of Wolaita zone (Figure 1), and 325 km south of Addis Ababa, capital of Ethiopia, with an average altitude of 1592 m asl. The farm has a gentle slope (4–6%) with monthly temperature ranging from 13 to 25°C and a bimodal rainy season with annual rainfall varying from 1184 to 1854 mm (Figure 2). According to [18], soils of the study area were grouped under "Sidralic Nitisols (Aric, Ochric)."

2.2. Sample Preparation and Soil Analysis.
Soil samples were collected at a depth of 0–20 cm with 10 subsamples to make a composited soil sample and were processed (air-dried, ground, and passed through 2 and 0.5 mm sieves) and analyzed for selected chemical and physical properties following the standard procedure.

Particle size analysis for textural class determination was conducted by the Bouyoucos Hydrometer Method with Marshall's Triangular coordinate system [19, 20] and the bulk density was determined using the Core method (volumetric cylinder method) [21]. Soil pH was measured using a glass electrode pH meter with a ratio of 1 : 2.5 soil to water [20] and soil electrical conductivity (EC) was measured using an EC meter with the ratio of 1 : 5 soil to water [22]. The soil organic carbon (OC) content was determined by the wet oxidation method [23] and the total nitrogen (TN) content by the Kjeldahl Method [24], available P, K, Ca, Mg, S, Cu, Fe, Mn, Zn, B, and Na were determined using Mehlich-3 method [25], and cation exchange capacity (CEC) was determined by the ammonium acetate method [22, 26]. The total soil P was

determined by perchloric acid digestion using the Olsen and Sommers [27] method as cited in [28]. Exchangeable acidity was determined by leaching with potassium chloride (KCl) followed by titration [22, 29, 30]. The general characteristics of the soil are presented in Table 1.

2.3. Lime Rates and Phosphorus Fractionation

2.3.1. Treatments and Experimental Design.
A completely randomized design (CRD) was used to compute the experiment statistics. The experiment employed four lime rates in three replications. The amount of lime required was calculated according to the Shoemaker-McLean-Pratt (SMP) [31] method of lime recommendation. The SMP [31] single-buffer procedure has been widely adopted and found to be particularly accurate for more acidic soils and frequently used in Ethiopia and in southern Ethiopia [16, 32]. The soil pH in the SMP buffer solution was 5.7, while it was 4.5 in water. This SMP single-buffer procedure uses a regression equation to calculate the required lime for different target pH values. In this case, the target pH in water was 6.5 and it was calculated by

$$LR(6.5) = 1.867(pHB)^2 - 31.82(pHB) + 131.23, \quad (1)$$

where LR (6.5) is lime requirement to bring soil pH to 6.5. pHB is the pH value by SMP buffer solution.

Thus, based on the calculation result, 10.5 t/ha $CaCO_3$ was used to bring the soil to the target pH (6.5 in water). Different rates were used as treatment, 0 t/ha (0%), 5.25 t/ha (50%), 10.5 t/ha (100%), and 15.75 t/ha (150%) $CaCO_3$.

2.3.2. Phosphorus Fractionations.
100 g of soil was placed into 200 ml polythene bags and each thoroughly mixed with equivalent weights of 100% pure fabricated lime rated as treatments (0, 50%, 100%, and 150% of lime rate). The samples were incubated for 30 days [33] approximately at field water holding capacity by applying and maintaining 60% of the total amount of water which was required to saturate the soil based on laboratory analysis. At the end of the period, chemical properties of incubated soil such as pH, P fractions, exchangeable bases, and acidity including some macro and microelements were measured.

The determination of P fractionation at different rates of lime followed the modified Chang and Jackson procedure as modified by [34]. In this procedure, the soil P is fractionated into soluble P (P-sol), aluminum bounded P (Al-P), iron bounded P (Fe-P), and calcium bounded P (Ca-P), but the residual P (Res-P) was estimated by calculating the difference between the total P and the sum of all fractions of inorganic P including organic P [35]. The organic P was estimated by the Kaila-Virtanen procedure [36]. Phosphorus in the extracts was measured using the ascorbic acid molybdenum blue method [16] and the area-based soil P fractions (kg P ha^{-1}) were calculated using the concentrations of soil P fractions and soil bulk density data.

(1) Fractionation of Inorganic Phosphorus. According to [34], 1.00 g of soil was placed into a polypropylene 100 ml centrifuge tube with 50 ml of 1 N NH_4Cl and shaken for
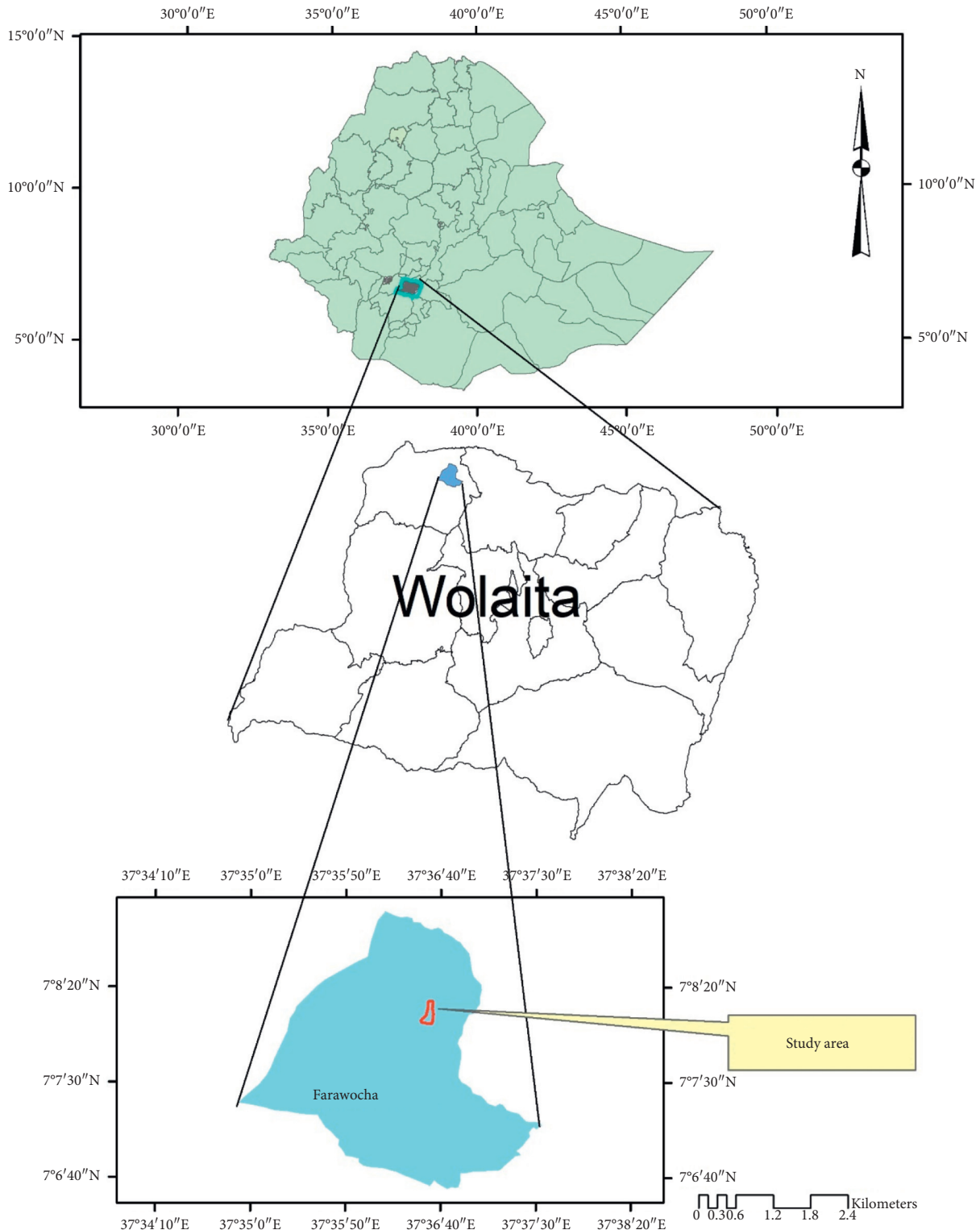
FIGURE 1: Map of the study area.

30 min to remove the easily soluble and loosely bound phosphorus (P-sol). The tube was centrifuged at 2,000 rpm for 10 minutes and the supernatant was reserved for spectrophotometer reading. To determine aluminum-associated P, 50 ml of 0.5 N NH_4F, which was adjusted to pH 8.2, was added to the residue from the previous extraction, shaken for 1 hr, and centrifuged for 10 min at 2,000 rpm. For the determination of Fe-associated P, the residue left from the extraction of Al-associated P was washed twice with 25 ml portions of saturated NaCl by centrifuging at 2,000 rpm for 5 min and then the decanted solution added to the NH_4F extract to make the volumetric flask to volume.
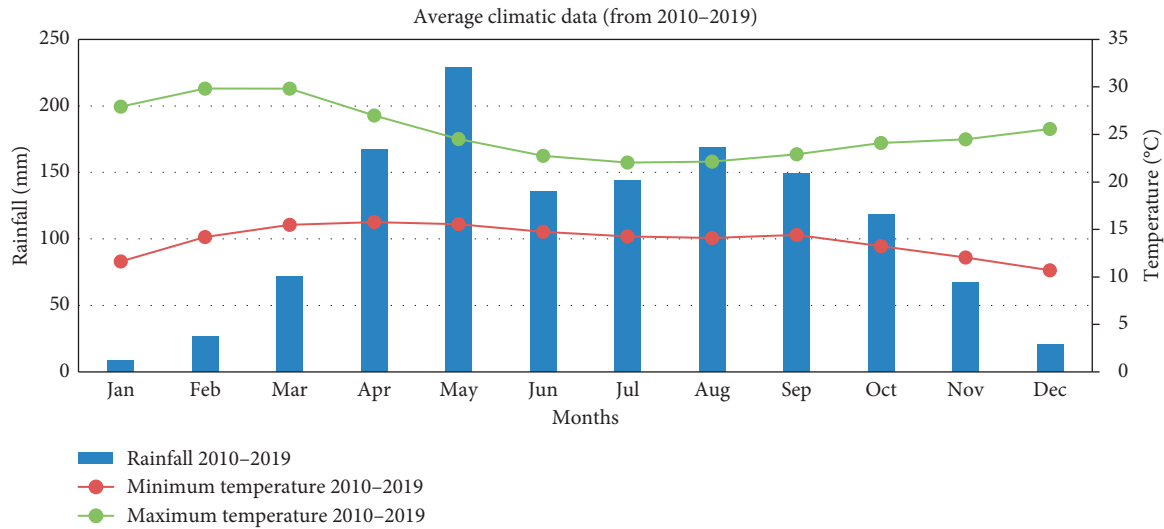
Average climatic data (from 2010–2019)

FIGURE 2: Climatic data of the study area (source: [17]).

TABLE 1: Surface soil characteristics before lime application.

Parameter	Unit	Soil
Soil particle size distribution		
Sand	%	24
Silt	%	24
Clay	%	52
Soil texture class		Clay
Bulk density	g/cm^3	1.2
pH (H$_2$O)		4.5
Electrical conductivity	ms/cm	0.06
Exchangeable acidity	cmol (+)/kg	4.2
OC	%	2.44
TN	%	0.17
Total P	mg/kg	357.5
Available P	mg/kg	3.2
Sulfur	mg/kg	29.5
Ca	cmol (+)/kg	2.44
Mg	cmol (+)/kg	0.33
K	cmol (+)/kg	0.67
Na	cmol (+)/kg	0.17
Ca saturation percentage	%	16.7
Mg saturation percentage	%	2.24
K saturation percentage	%	4.6
Na saturation percentage	%	1.2
Cation exchanging capacity	cmol (+)/kg	14.6
Percent base saturation	%	24.7
Bo	mg/kg	0.39
Fe	mg/kg	179
Ma	mg/kg	199
Cu	mg/kg	0.66
Zn	mg/kg	4.04

Then, 50 ml of 0.1 N NaOH was added, shaken for 17 hrs, and centrifuged for 15 min at 2,400 rpm and the decanted solution was reserved after it was made to volume with saturated NaCl after washing and centrifuging similarly as described above and the residue left for calcium-associated P extraction. 50 ml of 0.5 N H$_2$SO$_4$ was added, shaken for 1 hr, and then centrifuged for 10 min at 2,000 rpm. The washing procedure with saturated NaCl was done as described above.

(2) Fractionation of Organic Phosphorus. To determine Org-P, the Kaila-Virtanen procedure was used. Accordingly, Org-P was determined by subtracting P found in an unignited soil sample from ignited soil samples after digestion with 4 N H$_2$SO$_4$. One gram of soil (<0.5 mm) was ignited in a muffle furnace at 550°C for 2 h, with a gradual increase to the targeted temperature during the first hour, and then the temperature was maintained at 550°C for the last 1 h. After cooling, the ignited sample was digested by shaking with 30 ml of 4 N H$_2$SO$_4$ for 4 h and centrifuged for 10 min at 2,000 rpm. The unignited soil sample was also digested, shaken, and centrifuged similarly to the ignited sample [36] and then the difference between measured P from unignited soil sample and ignited soil sample was calculated as Org-P. The residual P was calculated as the difference between total P and total extracted P (Org-P, Al-P, Fe-P, and Ca-P) [37].

2.4. Statistical Data Analysis. Data were subjected to analysis of variance (ANOVA) following the standard procedure using Statistix version 8.0 software as described by [38]. Mean separation was done using least significant difference (LSD) at 5% of probability level whenever significant differences among treatment means were detected. In addition, descriptive statistics and Pearson correlation analysis were performed.

3. Result and Discussion

3.1. Phosphorus Fractions as Influenced by Liming Rates. All the P fractions significantly ($p < 0.05$) respond to lime application. The P pool in their increasing proportion in soil was Org-P > Res-P > Fe-P > Al-P > Ca-P > P-sol. This result is similar to the report in [14].

3.1.1. Soluble Phosphorus (P-sol). P-sol was the smallest of all P fractions and it was significantly ($p < 0.05$) affected by liming. It increased with increasing rates of lime from 3.13 (0% lime) to 4.28 mg/kg (150% lime) (Table 2; Figure 3). It also

TABLE 2: Effects of lime on phosphorus fractions (mean and percentage in brackets).

Lime rate (t/ha)	P_sol	Fe_P	Al_P	Ca_P	Res_P	Org_P
				(mg/kg)		
	3.13 c (0.88)	23.61 a (6.61)	9.97 a (2.79)	6.06 c (1.70)	35.54 c (9.94)	279.18 a (78.09)
5.25	3.67 b (1.03)	11.73 b (3.281)	6.74 b (1.89)	7.31 b (2.04)	67.20 b (18.80)	260.85 b (72.97)
10.5	3.85 ab (1.08)	10.32 b (2.89)	6.16 c (1.72)	9.48 a (2.65)	74.08 b(20.72)	253.61 b (70.94)
15.75	4.28 a (1.2)	9.80 b (2.74)	2.93 d (0.82)	9.79 a (2.74)	104.80 a (29.31)	225.90 c (63.19)
LSD 0.05	0.52	2.63	0.48	1.13	17.7	14.86
CV %	6.98	9.50	3.71	6.93	12.58	2.92

LSD (0.05): least significant difference at the 5% level; CV: coefficient of variation. Means in a column followed by the same letters are not significantly different at the 5% level of significance.
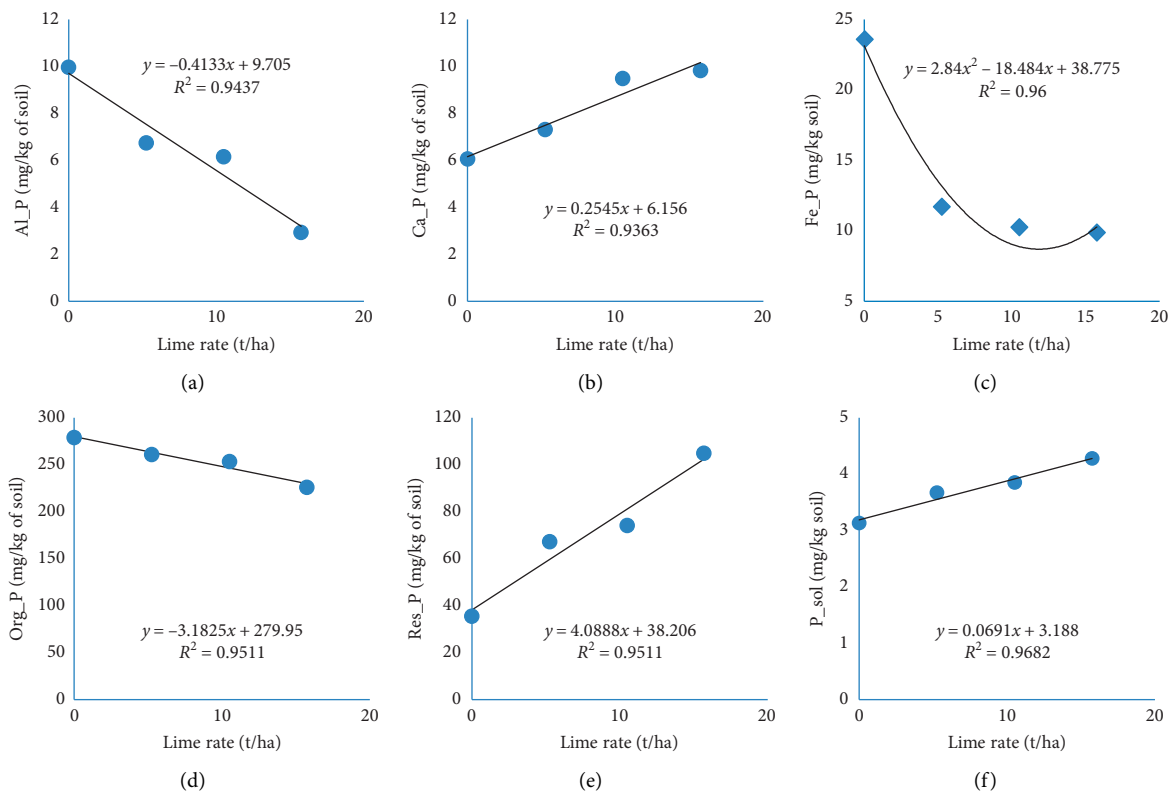

FIGURE 3: Effects of lime on (a) Al_P, (b) Ca_P, (c) Fe_P, (d) Org_P, (e) Res_P, and (f) P_sol.

showed positive relationship with lime ($r = 0.88^{***}$) (Table 3). Out of the total P, P-sol accounted for 0.88 to 1.2% (Table 2) and weighted 7.51 (no lime) to 10.27 kg ha^{-1} (150% lime). Reference [39] rated the P-sol (Olsen P) < 15 mg/kg as low and >30 mg/kg as extremely high. For the soils of the study area, it considered <36 kg ha^{-1} as low and >72 kg ha^{-1} as extremely high. Overall, lime resulted in more P-sol to the plant, yet it was not enough to meet the requirement by the plant even at a 150% lime rate. Thus, the soil should be supported by other soil management practices and external P fertilizers.

3.1.2. Iron-Associated Phosphorus (Fe-P). Among inorganic P fractions, Fe-P was the highest ranging from 23.61 mg/kg (unlimed) to 9.80 mg/kg (150% lime) and accounted for 6.61 to 2.74% of total P (Table 2). Its content significantly declined with increasing lime dose ($r = -0.83^{***}$) (Table 3; Figure 3). Through hydrolysis reaction of oxides and hydroxides of Al and Fe, the released H$^+$ lowered the soil pH and produced higher extractable Fe. Protonation in the soil with decreasing pH decreases the negative charge and increases the attraction to a positively charged surface [40]. As a result, the Fe-associated P was found to be relatively high [41]. But, with increased pH due to applied lime, Fe became insoluble and its activity was replaced by Ca^{+2}; then the P held by Fe decreased [42]. The changes in ionic composition due to changes in soil pH lead to a shift in chemical equilibria by increasing concentrations of dissolved Ca^{+2} and displaced hydrolytic Fe that can decrease the availability of P in the soil solution [43]. The decrease in Fe-P could be due to their precipitation as insoluble Fe(OH)^3 after the increased addition of liming material. Fe oxides become

TABLE 3: Correlation (Pearson) of lime with phosphorus fractions.

	Lime	Al_P	Ca_P	Fe_P	Org_P	Res_P
Al_P	−0.97***					
Ca_P	0.92***	−0.83***				
Fe_P	−0.83***	0.85***	−0.78**			
Org_P	−0.93***	0.96***	−0.79**	0.79**		
Res_P	0.94***	−0.97***	0.80**	−0.86***	−0.99***	
P_sol	0.88***	−0.88***	0.78**	−0.79***	−0.84***	0.86***

*Significance at the 5% level; **significance at the 1% level; ***significance at the 0.1% level. NS: not significant.

TABLE 4: Effects of lime on soil pH and exchangeable acidity.

Lime rate (t/ha)	pH (H_2O)	Exchangeable acidity (cmol(+)/kg)
0	4.55 d	4.18 a
5.25	5.38 c	0.73 b
10.5	6.09 b	0.23 c
15.75	6.60 a	0.23 c
LSD 0.05	0.04	0.11
CV %	0.38	4.10

LSD 0.05: least significant difference at the 5% level; CV: coefficient of variation. Means in the column followed by the same letters are not significantly different at the 5% level of significance.

more negatively charged with an increase in pH contributing to an increase in available P. Therefore, Fe bound P decreased as pH increased [44].

3.1.3. Aluminum-Associated Phosphorus (Al-P).
Al-P was the second-highest inorganic P fraction following Fe-P. It was affected significantly by lime ($p < 0.05$) with a correlation coefficient value of −0.97***. The Al-P ranged from 9.97 to 2.93 mg/kg for unlimed to 150%, respectively (Table 2; Figure 3). In proportion, it decreased from 2.79 to 0.82% (Table 2). In acidic soil, Al-P is higher than P-sol due to the content and reactivity of oxides, hydroxides, and oxyhydroxides of Al [45, 46]. Thus, the replacement of soluble Al^{3+} by Ca^{2+} on the exchanging site and precipitation of soluble Al^{3+} with the hydroxyl anions generated by carbonate hydrolysis in the soil solution from applied lime [47] might be due to the decreased level of Al-P with increasing rates of lime.

3.1.4. Calcium-Associated Phosphorus (Ca-P).
The Ca-P increased with the application of lime from 6.06 (unlimed) to 9.79 mg/kg (150% lime) which accounts for 1.70% to 2.74% (Table 2) and correlated positively with lime ($r = 0.92$***) (Table 3; Figure 3). It also weighed between 14.5 and 23.5 kg ha^{-1}. Even in acidic soil, Ca has an effect on the fixation of P; therefore, the application of lime increases soil pH and Ca, and, as a result, Ca-P increased [16, 48].

3.1.5. Residual Phosphorus (Res-P).
The value of Res-P was between 35.5 mg/kg (0%) and 104.8 mg/kg (150%) (Table 2) and constituted 9.94 to 29.31% of the total P and correlated positively with the lime ($r = 0.94$***) (Table 3). It was the second-largest P fraction after Org-P. The Res-P fraction, which is mainly composed of insoluble and stable forms of P,

such as Ca-, Fe-, and Al-bounded P, represents the unavailable forms of P pools in the soil. The increment of Res-P with increased rates of lime (Figure 3) can be due to the immediate complexation and reaction of both organic and inorganic released P with the surface of the clay [49–51]. Surface adsorption, so-called ligand exchange, and surface complexation [52] would be the mechanisms for the complexation of released P with the clay surface.

3.1.6. Organic Phosphorus (Org-P).
Organic P was found to be the highest among P fractions which ranges from 279 (0% lime) to 226 mg/kg (150% lime) (Table 2) and accounted for 78.1 to 63.2% of the total P and correlated negatively ($r = -0.93$***) (Table 3). In weight bases, it weighted between 670 and 542 kg ha^{-1}. The organic form of P is a significant and relevant source of soil P and contributes to the increase in available P (labile P) [53, 54].

From the total of soil P, 15–80% occurs in the organic form [55–57]. An increase in lime rate resulted in a significant decrease in the Org-P fraction ($p < 0.05$). The organic materials remained in the soil and the microbial mass may result in the Org-P to be the highest among others. This can be due to the increased activity of microorganisms in the improved environment by the application of lime. The microbes start to decompose and release P from organic material to the soil once the environment becomes conducive with the application of lime [58]. As a result, the amount of P held by organic material will be decreased [49].

3.1.7. Total Phosphorus.
The value of total P recorded in the studied soil was 357.5 mg/kg, which was below the concentration reported by [16]. This may be due to the nature and the status of exploitation of the soils.

TABLE 5: Correlation (Pearson) of lime with soil chemical properties.

	B	CEC	Ca	Cu	Fe	Lime	Mg	Mn	OC	TN	S	Zn	pH	K	Av. P	Ex. acidity	Ex. Al	Ex. H
CEC	0.4674[NS]																	
Ca	0.9250***	0.6151*																
Cu	0.9871***	0.5326[NS]	0.9634***															
Fe	−0.9693***	−0.4298[NS]	−0.9570***	−0.9803***														
Lime	0.9097***	0.6431*	0.9987***	0.9518***	−0.9415***													
Mg	0.9355***	0.6191*	0.9975***	0.9721***	−0.9582***	0.9952***												
Mn	−0.9727***	−0.6215*	−0.9430***	−0.9709***	0.9383***	−0.9368***	−0.9495***											
Oc	−0.7427**	−0.7876**	−0.9222***	−0.8030**	0.7899**	−0.9385***	−0.9087***	0.8370***										
TN	0.0415[NS]	0.0530[NS]	0.0009[NS]	0.0644[NS]	0.0402[NS]	0.0000[NS]	0.0228[NS]	0.0011[NS]	0.1045[NS]									
S	0.8995***	0.6172*	0.9869***	0.9432***	−0.9232***	0.9887***	0.9830***	−0.9153***	−0.9127***	0.1120[NS]								
Zn	0.9773***	0.4082[NS]	0.9471***	0.9845***	−0.9973***	0.9299***	0.9523***	−0.9371***	−0.7604**	0.0090[NS]	0.9163***							
pH	0.9456***	0.5862*	0.9941***	0.9725***	−0.9633***	0.9908***	0.9920***	−0.9576***	−0.8987***	0.0488[NS]	0.9873***	0.9569***						
K	0.8850***	0.5473[NS]	0.7397***	0.8387***	−0.7694**	0.7309**	0.7562**	−0.9149[NS]	−0.6150*	−0.0176[NS]	0.7115**	0.7787***	0.7743**					
Av. P	0.9358***	0.6397*	0.9931***	0.9676***	−0.9446***	0.9929***	0.9939***	−0.9636***	−0.9155***	0.0071[NS]	0.9801***	0.9378***	0.9900***	0.7935**				
Ex. acidity	−0.9752***	−0.4796[NS]	−0.8512***	−0.9421***	0.9042***	−0.8361***	−0.8652***	0.9667***	0.6756*	−0.0105[NS]	−0.8199***	−0.9144***	−0.8808***	−0.9630***	0.8825***			
Ex. Al	−0.4713[NS]	−0.2316[NS]	−0.6590*	−0.5629[NS]	0.6608*	−0.6522*	−0.6390*	0.4821[NS]	0.6253*	0.2407[NS]	−0.6055*	−0.6299*	−0.6159*	−0.1654[NS]	−0.6015*	0.3436[NS]		
EX. H	−0.9658***	−0.4776[NS]	−0.8322***	−0.9285***	0.8863***	−0.8173**	−0.8469***	0.9596***	0.6578*	−0.0114[NS]	−0.8013***	−0.8974***	−0.8640***	−0.9719***	−0.8672***	0.9992***	0.3112[NS]	
Na	−0.1520[NS]	−0.7923**	−0.4251[NS]	−0.2612[NS]	0.1798[NS]	−0.4616[NS]	−0.4244[NS]	0.2689[NS]	0.6396*	−0.2419[NS]	−0.4879[NS]	−0.1601[NS]	−0.3861[NS]	−0.0777[NS]	−0.4113[NS]	0.0716[NS]	0.2117[NS]	0.0580[NS]

*Significance at the 5% level; **significance at the 1% level; ***significance at the 0.1% level. NS: not significant.

Table 6: Effects of lime on soil available P, S, TN, and %OC (mean).

Lime rate (t/ha)	Ava. P	S	TN	OC
	mg/kg		%	
0	3.2 d	29.54 d	0.17 a	2.44 a
5.25	4.53 c	34.19 c	0.17 a	2.41 b
10.5	5.36 b	39.06 b	0.17 a	2.39 c
15.75	6.32 a	44.04 a	0.17 a	2.31 d
LSD 0.05	0.19	1.15	0.02	0.02
CV %	1.96	1.57	5.09	0.42

LSD 0.05: least significant difference at the 5% level; CV: coefficient of variation. Means in the column followed by the same letters are not significantly different at the 5% level of significance.

Table 7: Effects of lime on soil basic cations and CEC (mean).

Lime rate (t/ha)	Ca	Mg	K	Na	CEC
			cmol (+)/kg soil		
0	2.44 d	0.33 d	0.65 d	0.169 a	14.58 b
5.25	7.94 c	0.47 c	0.79 a	0.173 a	16.09 b
10.5	13.8 b	0.62 b	0.77 c	0.176 a	14.73 b
15.75	18.3 a	0.72 a	0.79 b	0.155 b	17.99 a
LSD 0.05	5.19	3.05	2.64	2.77	1.9
CV %	0.12	2.38	0.44	3.58	5.99

LSD 0.05: least significant difference at the 5% level; CV: coefficient of variation. Means in a column followed by the same letters are not significantly different at the 5% level of significance.

3.2. Effects of Lime on Chemical Properties.

Significant ($p < 0.05$) increase in soil pH and a decrease in exchangeable acidity were recorded with the application of lime (Table 4). Soil pH significantly correlated with r value of 0.99*** and increased from 4.5 to 6.6 but exchangeable acidity decreased from 4.18 to 0.23 cmol(+)/kg soil and negatively correlated with lime ($r = -0.84$***) (Table 5). Decreasing the content of exchangeable Al^{3+} and its precipitation with the hydroxyl anion through the replacement of Ca^{2+} from carbonate hydrolysis, the value of pH increased, and exchangeable acidity decreased [47, 48].

Lime also influenced ($p < 0.05$) OC, as well as available P and S (Table 6). Available P and S increased and correlated positively with increased lime (both $r = 0.99$***) and increased with liming from 3.2 to 6.32 mg/kg and 29.54 to 44.04 mg/kg, respectively. OC decreased from 2.44 to 2.31% and negatively correlated with increased lime ($r = -0.94$***) (Tables 5 and 6). The increased available P with an increased rate of lime can be due to the P released from Al and Fe because of improved pH by applied lime [59, 60]. Soil OC was decreased because of the decomposition of organic matter in the soil with an improved environment for the activities of microorganisms by the effect of lime [44]. Moreover, the OC increased with the increased lime application but decreased with respiration rate per unit biomass [61–63]. Sulfur also increased significantly with an increased rate of lime ($p < 0.05$) (Table 6). According to [60], S increased with increased lime rates because of the pH change and easy dissociation of organic matter by the microbial and biochemical attack and the consequent mineralization of S from the organic pool due to applied lime. Reduction in acidity because of change in pH with the application of lime increased the activity of microbes and increased N mineralization [44] but, with increased rates of

Table 8: Effects of lime on Fe, Mn, Cu, Zn, and B (mean).

Lime rate (t/ha)	Fe	Mn	Cu	Zn	B
			mg/kg		
0	178.69 a	198.78 a	0.66 c	4.04 d	0.39 c
5.25	156.61 b	167.17 b	0.79 b	4.30 c	0.47 b
10.5	129.82 c	159.84 c	0.88 a	4.60 a	0.51 a
15.75	130.60 c	150.16 d	0.90 a	4.57 b	0.51 a
LSD 0.05	2.99	3.33	0.02	$9.989E-03$	$9.989E-03$
CV %	1.01	0.99	1.47	0.11	1.06

LSD 0.05: least significant difference at the 5% level; CV: coefficient of variation. Means in the column followed by the same letters are not significantly different at the 5% level of significance.

lime, the microorganism activities and their increased population by the effect of lime could also be the reason for N immobilization [64]. This can explain the reason for the change in N in these acidic nitisols (Table 6).

The increasing lime rates (0% to 150%) increased Ca, Mg, and K contents with positive correlation values of 0.99***, 0.99***, and 0.73**, respectively (Tables 5 and 7), while the exchangeable Na and CEC showed no significant response for the applied lime. The finding was in agreement with [59] which reported that Na was not affected by the lime application. As reported by [65, 66] and [67], the application of lime increased Ca, Mg, and K contents. This is due to the increased base saturation as a result of pH change induced by lime application [59].

Copper, Zn, and B increased with increased lime rate; on the other hand, Fe and Mn contents were reduced (Table 8). Due to increase in pH by the application of lime, amounts of metal organic complexes of Cu steadily decreased; a two-fold

increase of OC content nearly doubled the share of Cu from organic matter in the total concentration of Cu in soil solution [68, 69]. In line with this study, the reports of [48, 70] stated that the significant reduction in Fe and Mn was due to increased lime application that makes iron and Mn be insoluble and replaced by Ca^{+2} ions found in lime [42, 71].

4. Conclusion

In this study, the fractions of P were identified and quantified and the effect of lime rates on P fractions and chemical properties were investigated. The result showed Org-P to be the largest among the fractions. Among inorganic P fractions, Fe-P was higher than Al-P and Ca-P, whereas P-sol was observed to be the smallest fraction. The application of lime significantly influenced the P pool and its availability. Liming resulted to be significantly and positively correlated with P-sol, Ca-P, and Res-P but a negative correlation was observed with Fe-P, Al-P, and Org-P ($p < 0.05$). Although the effect of lime enhanced the level of P-sol, the change was not found to be enough to satisfy the need of the plant even at 150%. This showed that the study soil was originally poor in available P. The soil pH markedly affected most of the chemical properties and the lime application significantly changed the pH and mitigated the status of essential nutrient elements. Therefore, liming of these acidic nitisols at 100% is suggested because the changes in most of the chemical properties due to applied lime, especially the P-sol, were not significant between 100 and 150% lime rates. It is concluded that application of external fertilizer is suggested to meet the P requirement of the plant. In addition, assessing the P dynamics under field condition, long period of incubation, or concurrent use of other soil management practices is suggested.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

The authors collected, analyzed, interpreted, and prepared the manuscript.

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