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Research Paper

Effects of Soil Fertility Management Practices on Phosphorus Adsorption–Desorption Dynamics of Acidic Soil, the Case of Gimbo District, Southwest Ethiopia

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Abstract

This study examined the effects of various soil fertility management practices on the adsorption-desorption behavior of different phosphate fertilizers in acidic soils, which are known for their high phosphorus (P) fixation. Top surface soil samples (0-20 cm) from farmer fields were collected and incubated for 40 days, for batch type adsorption-desorption experiments. Adsorption data were obtained by equilibrating the respective soil samples for 24 h at room temperature with 30 ml of 0.01 M $CaCl_2$, containing 0, 25, 50, 75, 100, and 125 mg kg^{-1} of applied external P as KH_2PO_4, NPSB (Nitrogen, Phosphorus, Sulfur and Boron blended fertilizer) and DAP (Diammonium Phosphate). The combined application of lime and compost significantly increased soil organic carbon, available P, and total P. Phosphorus adsorption varied by soil and fertilizer types, with the total mean performance ranked as NPSB > DAP > KH_2PO_4, except for the last two treatments in Michit soil. The combined application of lime and compost notably reduced external P requirements. In contrast, there was an increase in phosphorus desorption. Soil pH and organic carbon showed strong positive correlations with higher P desorption. Phosphorus adsorption and desorption capacities were influenced by combined application of different fertilizers and they varied across soils types and fertilizer sources. Desorbed amounts of phosphorus were increased following application of DAP, NPSB, and KH_2PO_4 fertilizers. It is suggested to conduct field experiments with the external phosphorus requirement (EPR) to validate the effectiveness of each fertilizers amount under real-world conditions.

1. Introduction

Soil acidity poses a significant risk to crop productivity and the long-term viability of phosphorus in agricultural systems (Liao et al., 2024). This can occur naturally but is often accelerated by human activities (Chen et al., 2022). Generally, phosphorus is highly retained by adsorption sites in acidic soil, the quantity of which can differ significantly between soils (Asomaning, 2020). When a phosphorus fertilizer is applied to acidic soil, only a small fraction dissolves for crop utilization (Uzoho, and Oti, 2005). 80% of the applied phosphate is not available for crop uptake in tropical acid soil (Berhanu & Eyasu, 2021).

Soil acidity can be improved by applying lime, and organic fertilizer sources while phosphate fertilizers are

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commonly used to increase the availability of soil phosphorus to optimal levels by minimizing the sorption capacity of the soil (Yang et al., 2019; Redi, 2022). Soil fertility amendments affect phosphorus fractions and their sorption properties influence phosphorus use efficiency and overall productivity (Ding et al., 2023; Otieno et al., 2023). Phosphorus adsorption and desorption in soil play a crucial role in soil fertility issues and problems, and influence the environmental behavior of phosphorus (Yang et al., 2019), directly affecting the phosphorus availability to the crop (Tang et al., 2022). This depends mainly on the initial pH, P-concentration, and adsorption temperature (Biswas et al., 2023).

Phosphate desorption in soil can be promoted by increasing the negative charge on soil particle surfaces, either by increasing the pH of the solution or by introducing a competing anion (Redi, 2022). Therefore, combined use of lime and compost could significantly alter the chemistry of acidic soils. Lime, containing calcium and/or magnesium ions, helps to displace H^+, Fe^{3+}, and Al^{3+} ions from soil colloids, reducing phosphorus sorption (Kisinyo et al., 2013), and it shows synergistic interactions with applied nutrients and increased nutrient uptake by plants (Chintala et al., 2012). In addition, the application of compost improves soil fertility parameters, such as alleviating acidification, increasing soil organic matter, phosphorus availability, and sustainable increase in crop yields (Ferri et al., 2010). The type of phosphorus fertilizer used affects phosphorus fixation in soils. In acidic brown hill soils, phosphorus adsorption from the solution decreases in the order of $NH_4H_2PO_4$, KH_2PO_4 and NaH_2PO_4. The low availability of inorganic phosphorus, and its adsorption-desorption properties in soil are often the limiting factors for phosphorus utilization efficiency and crop productivity (Tang et al., 2022).

In south southwestern part of Ethiopia, soil fertility degradation due to acidity is a serious problem (Mathewos et al., 2020). Specifically, in the Kafa zone, most farmers usually apply phosphorus fertilizers without judging the P status of the soils for which the P adsorption study has a significant role to play. Farmers use Nitrogen, Phosphorus, Sulfur and Boron blended fertilizer (NPSB) fertilizers with Diammonium Phosphate (DAP) in acidic soils, which may have negative consequences than the intended use. Limited work has been carried out to understand the relationship between the P sorption capacity and specific soil properties in the research area. A proper understanding of phosphorous sorption-desorption properties in acidic soils is important for P fertilizer management practices (Redi, 2022), and for moving away from blanket fertilizer recommendations to soil or site specific fertilizer management (Berhanu & Eyasu, 2021). Furthermore, there is no research that has been conducted on the effect of combined application of coffee husk compost, and lime on phosphorus adsorption-desorption capacity of acidic soil.

Therefore, the objective of the current study was to investigate adsorption-desorption capacity of phosphorus in acidic soil by using DAP, NPSB and KH_2PO_4 as external phosphorus source. As the operational steps of the objective, the relationship between P sorption and soil properties in acid soils, management effect on phosphorus adsorption-desorption parameters, and external phosphorus requirement of the three fertilizers were investigated. The study provided practical recommendations for selecting and applying phosphate fertilizers to minimize P fixation and maximize bioavailability, enhancing nutrient use efficiency and crop productivity in acid soils.

2. Materials and Methods

2.1 Site description and soil sampling

The study was conducted on the acid soil of Gimbo District, Kafa Zone, southwestern Ethiopia, which is located about 461 km southwest of Addis Ababa. It is situated between 07° 23'N to 07° 49' N latitude and 36° 00'E to 36° 47'E longitude with altitudinal range of 500 to 3300 m a.s.l. The study area is characterized by a variety of landforms resulting in a highly diverse climate, soil, and vegetation. Topographically, it is characterized by a complex system of highlands, steep valleys, and large flatlands, which drop to the lowlands in the South. The area has a long rainy season (March–October) and receives a mean annual rainfall ranging from 1710 to 1892 mm. The dry months are December–February. The annual mean temperature is 19.4°C with average maximum and minimum temperatures of

27.5˚C and 10.1°C, respectively (Mulatu et al., 2020).

2.2 Soil sampling, and compost preparation

Soil samples were collected from farmers' fields in the district. By walking in a zig-zag pattern in the field, subsamples were taken at randomly marked points using an auger to a depth of 20 cm, after scraping the surface litter. Composite soil samples were prepared from 15 to 20 subsamples. Finally, approximately 1 kg of soil was collected from the bulk composite soil sample using a quartering method. The samples were air dried, crushed using pestle and mortar, and passed through a 2 mm sieve for the analysis of selected physical and chemical properties. In the laboratory, samples were grouped based on their acidity level into strongly acidic (pH 5.1 to 5.5), moderately acidic (pH 5.6 to 6), and slightly acidic (pH 6.1 to 6.6) and represented by Michit, Ufudo, and Keyakela, respectively. Coffee husk, vegetable waste, chicken and animal manure were collected from Bonga town, mixed well, and composted in 2 m x 3 m pits for 60 days. Temperature and aeration were managed during composting, and the moisture content was also maintained between 60 and 65 ^{0}C.

2.3 Incubation experiment and design

Air-dried and sieved soil sample (500 g) were placed separately in a plastic container. The lime requirement of each soil sample was calculated using the equation used by Erkihun et al. (2022), and mixed with compost. The amount of compost was determined based on the equivalent amount of nitrogen in mg kg^{-1} of each soil sample. Then lime and compost obtained were mixed with the soil three soil types. For Michit soil, 1.7 g of lime and 1.2 g of compost, for Ufudo 0.56 g of lime and 1.18 g of compost, and for Keyakela 0.02 g of lime and 1.23 g of compost were mixed with 500 g of the soil. Three replications of the mixtures of soil, compost, and lime were placed in the laboratory, following a completely randomized design, at 25˚C for a 40-day incubation period. During the incubation period, deionized water was added until 60% of the field capacity was reached, and then the surface was covered with porous plastic films to allow gas exchange and to minimize moisture loss. The plastic container was weighed every three days and water was added to maintain a constant moisture content throughout the experiment. After incubation, the soil samples were air-dried and passed through a 0.25- mm sieve before use. Later, the soil samples were used to determine the effect of mixed application of lime and compost on selected soil properties and phosphorus adsorption and desorption experiments.

2.4 Soil and compost analysis

For the analysis of organic carbon (OC) and Total Nitrogen (TN), soil samples were passed through a 0.5 mm sieve. The soil reaction was determined by measuring the pH of soil/water at a ratio of 1:2.5 using a pH meter. Organic carbon (OC) and TN were determined by using the wet oxidation and Kjedahl methods, respectively. Available phosphorus was determined by the Bray II method. For total P determination, samples were digested by the H_2O_2-H_2SO_4.

2.5 Phosphorus adsorption-desorption studies

The phosphorus adsorption study was conducted by batch type (Tamungang et al, (2016); following the procedure of Ochwoh et al. (2016). Phosphorus solutions of 0, 25, 50, 75, 100, and 125 mg P L^{-1} concentrations of were prepared using KH_2PO_4, DAP, and NPSB in distilled and deionized water. Then, two grams of air-dried incubated soil sample was accurately weighed into 50 mL centrifuge tubes in triplicate. Thirty milliliters of the prepared P solution in 0.01 M $CaCl_2$ were added to the soil in respective centrifuge tubes. The mixture was shaken for 24 h at 25 ^{0}C on an end-to-end shaker (Edmund Buhler SM 25) at 125 rpm.

After equilibration, the soil suspension was immediately filtered through Whatman No. 42 filter paper and centrifuged at 3000 rpm for 30 min to obtain a clear solution. Five milliliters of the extract from each sample and blank were pipetted into test tubes. Then, 2.5 mL of ammonium molybdate solution was prepared in 10 % sulfuric acid and potassium antimony tartrate, 2.5 mL of ascorbic acid and 10 mL of distilled water was successively added to the extracts in each test tube and mixed. The test tubes were placed in a water bath at 85 ^{0}C for 10 min to enhance color development.

After the blue color had developed, phosphorus concentration was measured using a UV-Vis spectrophotometer at a wavelength of 882 nm. Then, the adsorbed phosphate was calculated from the difference between the initial and final phosphorus concentrations in the solution using Eqn. (1).

$$Q = (C_i - C_f)\frac{V}{M} \quad (1)$$

where, Q is the phosphorus sorbed (mg kg^{-1}); C_i and C_f are the initial and final phosphorus concentrations (mg L^{-1}), respectively; V is the volume of the experimental solution (L), and M represents soil mass (kg).

The equilibrium sorption data were analyzed using Langmuir and Freundlich isotherm models. Eqn. (2) gives the Langmuir isotherm:

$$q_e = \frac{q_{max}K_L C_e}{1+K_L C_e} \quad (2)$$

where, qe is the phosphorus adsorbed (mg kg^{-1}) in the soil solid phase in equilibrium with phosphorus concentration (mg/L) in the soil solution (Ce), $Qmax$ represents the phosphate adsorbed capacity of the soil, and K_L is a constant related to the binding energy-based the suggestion.

The linear form of the Langmuir equation is given by Eqn. (3).

$$\frac{C_e}{Q_e} = \frac{C_e}{Q_{max}} + \frac{1}{Q_{max}K_L} \quad (3)$$

where, the plot of Ce/qe against Ce is a straight line; $qmax$ can be obtained from the slope of the line and KL can be obtained from the intercept. The slope of the line gives $1/qmax$, whereas the intercept gives $1/qmaxKL$.

The external phosphorus requirement (EPR) was calculated by rearranging Eqn. (2) to the linear form of Langmuir Equation for each soil sample and fertilizers at 0.2 mg P L^{-1} of equilibration. The amount of desorbed phosphorus (mg kg^{-1}) was determined using the formula described by Sun et al. (2020):

$$D = \frac{C_{ed}*V}{M} \quad (4)$$

where, D (mg kg^{-1}) is the amount of phosphorus desorbed from the soil at the equilibrium P concentration Ced (mg L^{-1}), and V and M are the volume of solution in liter and mass in kilograms, respectively.

Desorption can be described by the Langmuir equation as:

$$C / D = C / Dm + 1 / kDm \quad (5)$$

where C (mg L^{-1}) is the amount of P desorbed from the soil at the equilibrium P concentration, k (L mg^{-1}) is a constant related to the desorbing strength, and Dm (mg kg^{-1}) is the maximum amount of desorbed phosphorus.

2.6 Data analysis

The data was analysed with R software and SPSS version 27. Analysis of variance at significant levels at P≤ 0.001, 0.01 and 0.05 was performed for multiple comparison tests. Linear regression techniques were used for model validation and to determine the functional relationship between the model parameters and selected soil properties.

3. Results and Discussion

3.1 Effect of integrated application of lime and compost to the selected soil properties

Soil pH showed significant change after integrated application of lime and compost in the three soil groups (Table 1). In the study by Erkihun et al. (2022) also the soil pH increased by liming. Integrated application of lime and compost increased soil organic carbon, available phosphorus, and total phosphorus in all soil as compared to the control. The soil organic carbon increased by 72.52, 80.36, and 38.94 % for Michit, Ufudo, and Keyakela soil, respectively. These results agree with the findings of Biruk et al. (2017), who reported that the combined application of lime and compost enhanced soil organic carbon in acidic soils. The available phosphorus was increased by 1.75,1.77, and 2.37 times in Michit, Ufudo, and Keyakela soil samples. The total phosphorus also increased for the three soil types. The phosphorus activation coefficient (PAC) is the ratio of available phosphorus to total phosphorus, and it can represent the transformations between total phosphorus and available phosphorus (Wu et al., 2017). When PAC was less than 2.0%, the total phosphorus is not easily converted to available phosphorus (Cui et al., 2018). The integrated application of lime and compost increased the phosphorus activation coefficient in Michit and Keyakela; however, it was decreased in Ufudo, which could be affected by both soil types and fertilization treatments (Wu et al., 2017).

Table 1: The effect of integrated application of lime and compost to selected soil properties

Site	Treatment	pH: H_2O	Organic C (%)	Total N (%)	Available P (mg kg^{-1})	Total P (mg kg^{-1})	PAC
Michit	NLC	5.28±0.22	3.02±0.28	0.29±0.02	18.08±6.4	123.42±0.05	0.147
	WLC	6.46±0.34	5.21±0.25	0.449±0.55	31.68±0.57	147.03±0.01	0.152
Ufudo	NLC	5.69±0.08	2.75±0.09	0.27±0.36	15.6±0.03	145.87±0.06	0.107
	WLC	6.45±0.4	4.96±0.5	0.428±0.09	27.64±0.22	309.20±0.04	0.09
Keya-kela	NLC	6.25±0.21	3.39±0.66	0.259±0.03	25.65±22	150.72±0.08	0.17
	WLC	6.67±0.07	4.71±0.45	0.406±0.10	59.391±0.4	189.88±0.02	0.313

Note: NLC; without lime and compost, WLC; with lime and compost.

3.2 Phosphorus adsorption characteristics

3.2.1 Effect of combined application of lime and compost to phosphorus adsorption characteristics

The sorption isotherm with integrated application of lime and compost to soil had a significant ($P>0.05$) effect on the total mean of phosphorus adsorption in the three soil types (Table 2). The location and source of different phosphate fertilizer treatments influence phosphorus adsorption, as the more phosphorus was added the more it was adsorbed. In Michit, the mean adsorption of P in DAP increased significantly with the increased rate of phosphorus addition; however, the total mean of adsorption was not significant before and after the treatment of lime and compost application. For the phosphorus in NPSB and KH_2PO_4, the total mean of phosphorus adsorption was significant, before and after treatment, with lime and compost at ($P\leq0.001$).

The total mean adsorption of phosphorus in DAP and KH_2PO_4 was significantly ($P>0.05$) decreased after the integrated application of lime and compost but the total mean of phosphorus adsorption in NPSB declined insignificantly at $P\leq0.001$, $P\leq0.01$, and $P\leq0.05$, in Ufudo soil. In Keyakela soil, which is slightly acidic, the integrated application of lime and compost significantly ($P>0.05$) affected the total mean of phosphorus desorption in DAP, NPSB, and KH_2PO_4. Thus,the total mean of phosphorus adsorption in KH_2PO_4 ≥ NPSB ≥ DAP to Michit and Ufudo soil but for Keyakela soil, total mean of phosphorus adsorption in KH_2PO_4 ≥ DAP ≥ NPSB (Table 2). Under the equal phosphorus fertilizers treatment, the adsorption of phosphorus by the soil from different phosphate fertilizers was different, and the overall performance was NPSB > DAP > KH_2PO_4, except at the last two treatments in Michit soil. For all fertilizer applied treatments, the total means of adsorption in strongly acidic soil was greater than those in moderately and slightly acidic soils. This is probably because the dominance of a positive charge on the surface of the colloid enhanced the adsorption of phosphate anions, and as the pH increased and the surface charge became more negative, the dianion of phosphorus (HPO_4^{2-}) increased, the monovalent anion decreased (H_2PO_4), and the adsorption of P anions decreased (Sun et al., 2020).

3.3 Phosphorus adsorption parameters

The data shown in Table 3 indicate that these Langmuir and Freundlich adsorption equations fit the phosphorus adsorption isotherms for different soils well. The mean of the Langmuir regression analysis value was higher than that of the Freundlich regression analysis and the root mean square error of linear Langmuir fitting was significantly lower than that of the Freundlich linear fitting. Hence, the Langmuir model can be considered a superior model for describing the phosphorus adsorption capacities of soils in the study area. The maximum adsorption capacity for phosphorus (Qmax), phosphorus bonding energy constant (k), and soil buffering capacity (MBC) calculated from Langmuir adsorption isotherms have generally been used to determine the availability of phosphorus in soil and the external phosphorus requirement of soil (Yang et al., 2019). The maximum adsorption capacity of phosphorus (Qmax) reflects the number of P adsorption sites per unit weight of soil (Johan et al., 2022). In this study, it varied from soil to soil, and source fertilizers, and it was affected by the integrated application of lime and compost.

Table 2: Effect of integrated application of lime and compost on different phosphatic fertilizers adsorption (mean ±std)

Site	Fertilizer type	Fertilizer rate (mg l^{-1})					Average
		25	50	75	100	125	
Michit	DAP	368.53±3.53m	689.84±16.00ij	944.46±61.58gh	1200.88±45.60f	1452.31±7.72c	931.20±393.73c
	NPSB	364.61±3.72m	667.77±90.28ijk	982.54±109.36g	1326.88±25.16d	1531.52±2.38b	934.89±430.65ab
	KH_2PO_4	370.43±1.38m	709.66±8.37g	968.64±32.19g	1266.55±16.27de	1598.66±51.25a	1021.28±454.24a
	DAP with lime & compost	342.91±0.94m	688.24±2.21ij	991.44±1.18g	1231.40±1.48ef	1419.20±74.5c	934.64±+398.39c
	NPSB with lime & compost	342.30±0.83m	587.98±13.14l	902.60±1.31h	1283.82±18.23de	1629.42±3.96a	949.22±480.18bc
	KH_2PO_4 with lime & compost	337.8±1.33m	639.53±11.53gkl	621.63±24.47kl	962.28±22.25g	1284.95±12.24de	769.24±336.65d
	R						0.995
	CV (%)						3.7
	Interaction b/n fertilizers, management, and rate						***
Ufudo	DAP	352.52±8.04f	667.72±+42.64e	929.74±83.49d	1167.90±78.12c	1438.88±10.32b	911.35±394.50a
	NPSB	363.42±8.60f	696.77±20.65e	1008.74±78.5d	1201.09±277.5c	1433.87±343.08c	905.56±406.65a
	KH_2PO_4	359.93±1.54f	683.16±46.83e	943.88±32.16d	1258.52±+7.62	1582.82±78.32c	1004.23±+456.33a
	DAP with lime & compost	324.31±0.94f	400.09±3.43f	622.4±17.68e	906.49±23.4dc	1173.44±162.96	685.35±334.17b
	NPSB with lime & compost	311.42±1.08f	675.69±2.7e	983.74±2.38d	1282.87±6.09c	1426.82±+10.8	936.11±419.56a
	KH_2PO_4 with lime & compost	336.76±2.09f	576.6±7.74e	553.89±13.38e	913.15±44.69d	1287.46±7.28c	733.58±344.84b
	R						0.973
	CV (%)						9.24
	Interaction b/n fertilizers, management, and rate						*
Keyakela	DAP	352.76±2.89m	655.14±3.87j	813.52±42.32i	1087.31±0.25de	1442.45±3.3b	870.24±+385.37c
	NPSB	360.63±8.65m	699.05±9.31j	1028.30±16.20ef	1111.58±156.16c	1127.93±147.85d	846.75±317.84c
	KH_2PO_4	363.30±0.68m	700.13±2.58j	952.34±5.80gh	1257.91±22.68c	1465.56±227.08a	980.20±424.95a
	DAP with lime & compost	262.72±13.86o	441±1.08l	658.82±39.64j	907.35±1.31h	1230.8±1.31c	700.14±354.33d
	NPSB with lime &compost	336.76±0.65mn	591.96±2.56k	980.97±1.95fg	1257.27±4.71c	1539.62±2.7a	941.31±450.46b
	KH_2PO_4 with lime & compost	283.13±+1.3m	370.16±6.53m	538.93±14.25k	904.67±13.52gh	1256.57±8.56c	670.69±374.99e
	R						0.994
	CV (%)						4.46
	Interaction b/n fertilizers, management, and rate						***

Note: Different uppercase letters in the column, different lowercase letters in both column and rows, and lowercase letters as a superscript in a row indicate a significant difference among means using Tukey's HSD test; CV, coefficient of variation, Significant a code: at P ≤0.001 '***' P ≤0.01 '**' 0.01, P ≤0.05 '*'

The Qmax values for the different treatments across the site ranged from 909.09 to 2380.95 mg Kg^{-1}. The variations might be associated with the site, size of phosphate ions dissociated from each source of fertilizers, and pH of equilibrium solutions (Lemma et al., 2015). In Ufudo and KH_2PO_4 treatment in Michit soil, the adsorption maximum of soil increased after integrated application of lime and compost to Keyakela, and Michit soils. This is probably due to the increase in soil surface area through the application of organic fertilizer, which increased the physicochemical adsorption of phosphorus (Mengmeng et al., 2020). Overall, the highest adsorption maximum was observed in the Keyakela soil after treatment with NPSB fertilizer. This was probably due to the presence of sulfur molecules in the NPSB fertilizer. For each molecule of S added to soil, two H^+ ions will be generated (Iqbal et al., 2020), and an increase of positive charge on the surface of the colloid enhanced the adsorption of phosphate anions (Sun et al., 2020). In contrary, studies in southern highlands of Ethiopia reported low value of adsorption maximum (680.22 to 1112.11 mg kg^{-1}) (Bereket et al., 2018). The varying Qmax values may be due to variations in soil properties from location to location and the effect of model used.

The bonding energy constant (K_L) is one of the most important parameters of the P adsorption affinity of soils and it varies depending on the type of interaction between the adsorbate and the adsorbent (Wang and Liang; 2014; Tamungang et al., 2016). Relatively, higher K_L value indicate that the degree of spontaneous reaction is stronger and weaker P supply intensity (Tang et al., 2022). In this study, relative to the control, the K_L value was smaller after integrated application of compost and lime in contrast to the, adsorption maximum (Table 3). This indicates that greater phosphate desorption after integrated application is probably due to organic acids from compost increasing the negative charge on the soil colloid (Whalen & Hendershot, 2007). MBC is an integrated parameter that combines Qm and K_L (Wang & Liang, 2014), and it varied significantly and depends on the types of fertilizers used (Ahmed et al., 2021).

A higher MBC indicates that more phosphorus is adsorbed. In contrast, adsorption maximum, bonding energy constant (K_L) and MBC values in all the three-soil types decreased after lime and compost application. In line with this, Fang et al. (2020) reported that organic amendment is beneficial for soil health and it leads to a decrease in the soil surface area available for nutrient adsorption, thereby reducing MBC. Wichern et al. (2020) noted that amendments can alter the soil pH and reduce the availability of certain adsorption sites on soil particles, thus lowering MBC. Similarly, Tang et al., (2022) reported that organic materials treatments reduced the MBC of the soils for P. Higher application of lime lowered both k and MBC (Sukyankij et al., 2024). The higher value of MBC for the soil without any amendment suggests the need of higher applications of phosphorus fertilizers to mitigate soil P sorption affinity and to maintain a desired P concentration in soil solutions. Soils with a high buffering capacity tend to fix high levels of phosphates highly (Tamungang et al., 2016). Phosphorus fixing capacity of soil could be minimized through soil fertility amendment.

3.4 External phosphorus requirement (SPR)

The amount of P adsorbed at 0.2 mg L^{-1} equilibrium solution P concentration is generally accepted as EPR of soil for optimum crop yield. For all soil types and fertilizers sources of this study, the combined application of lime and compost significantly ($P>0.05$) reduced the external phosphorus requirement, showing notable variation before and after treatment. It also varied from site-to-site and from fertilizer to fertilizers (Table 3). Various studies have reported EPR within different ranges. Zinabu et al. (2015) found that the EPR for soils in southern Ethiopia ranges from 50 to 201 mg P/kg, while (Berhanu & Eyasu, 2021) reported a range of 25–32 mg Pkg^{-1}. The external phosphorus requirement for DAP fertilizer decreased significantly by 62.77, 16.13, and 15.63 % in Michit, Ufudo, and Keyakela, respectively. The phosphorus requirement for NPSB fertilizer decreased by 37.33, 31.91, and 19.91% in Michit, Ufudo, and Keyakela, respectively. For KH_2PO_4, the reductions were 27.45, 38.39, and 9.26% in Michit, Ufudo, and Keyakela, respectively (Table 3). Thus, external phosphorus requirement is influenced by the management and type of phosphate fertilizers used.

Table 3: Effect of integrated application of lime and compost to Langmuir and Freundlich adsorption parameters

Site	Treatment	Langmuir equation $C/Q = C/q_{max} + 1/K1q_{max}$	Qmax	K1	MBC	EPR (mg/kg)	EPR (Kg/ha)	R^2	Freundlich equation $Q = KfC^n$	R^2	EPR, mg/kg
Michit	DAP	0.00067Ce +0.0016	1471.43	0.41	609.17	112.52	247.5	0.964	$478.63C^{0.321}$	0.996	285.516
	NPSB	0.00060Ce +0.0018	1667.59	0.33	548.64	102.95	226.5	0.974	$400.968C^{0.449}$	0.977	194.658
	KH2PO4	0.00068Ce+0.0012	1477.90	0.59	869.01	155.51	342.1	0.955	$521.795C^{0.337}$	0.953	303.352
	LC, DAP	0.00062Ce+0.0027	1612.90	0.23	369.35	70.64	155.4	0.998	$389.22C^{0.41}$	0.647	201.20
	LC, NPSB	0.00055Ce+0.0051	1818.18	0.11	196.36	38.44	38.44	0.600	$297.09C^{0.49}$	0.792	135.02
	LC, KH_2PO4	0.00097Ce+0.0045	1030.93	0.22	222.68	42.69	93.90	0.86	$322.78C^{0.30}$	0.663	199.17
Ufudo	DAP	0.00065Ce +0.0029	1528.37	0.22	339.30	64.98	146.9	0.968	$294.924C^{0.468}$	0.996	138.865
	NPSB	0.00066Ce+0.0016	1506.36	0.41	617.61	114.16	258.0	0.989	$434.78C^{0.0374}$	0.986	409.381
	KH_2PO_4	0.00065Ce +0.0018	1535.63	0.35	543.61	101.53	229.5	0.934	$364.645C^{0.468}$	0.949	171.693
	LC, DAP	0.00072Ce+0.019	1388.89	0.04	52.78	10.48	23.70	0.78	$218.27C^{0.35}$	0.647	124.27
	LC, NPSB	0.00048Ce+0.0054	2083.33	0.09	185.42	36.43	82.33	0.93	$239.08C^{0.59}$	0.792	92.502
	LC, KH_2PO_4	0.0011Ce+0.0049	909.09	0.22	203.64	38.98	88.10	0.82	$297.92C^{0.29}$	0.663	186.81
Keyakela	DAP	0.00078Ce+0.0031	1280.63	0.26	326.56	62.14	135.5	0.929	$299.778C^{0.402}$	0.912	156.969
	NPSB	0.00086Ce+0.0011	1158.10	0.79	917.22	158.36	345.2	0.999	$454.109C^{0.277}$	0.812	290.767
	KH_2PO4	0.00065Ce+0.0018	1531.50	0.37	562.06	104.73	228.3	0.942	$403.395C^{0.415}$	0.967	206.851
	LC, DAP	0.000594Ce+0.02014	1683.50	0.03	48.82	9.71	21.17	0.85	$58.95C^{0.62}$	0.97	21.73
	LC, NPSB	0.00042Ce+0.0063	2380.95	0.07	159.52	31.48	68.63	0.99	$251.4C^{0.56}$	0.861	102.08
	LC, KH_2PO4	0.000615Ce+0.083	1626.02	0.03	55.28	9.70	21.15	0.78	$105.41C^{0.54}$	0.60	44.20

Note: LC: lime and compost application.

The relatively higher EPR values of Michit soil may be attributed to the lower pH values, which is consistent with the study by Mnthambala et al. (2017). The implication of soil organic matter contents in P sorption and external P requirement cannot be ruled out. The extent to which the relative concentrations of phosphate ions in the solutions were influenced by the pH of the ambient solution was self-evident. The increase in P sorption and EPR with decreasing soil pH and the decrease in P sorption and EPR with increasing soil pH may be attributed to the amphoteric behavior of soil colloids in such soils. Generally, soils that desorb less than 150 mg P kg^{-1} are classified as having low P sorption, therefore, P adsorption in this study area was low. In general, as shown in Table 3, the P sorption affinity, P adsorption maxima and EPR values were significantly low after the mixed addition of lime and compost.

3.5 Phosphorus desorption isotherms

Desorption is more significant than adsorption because it allows for the reuse of immobilized P in soil (Yang et al., 2019). The amount of phosphorus desorbed from the soil was consistently lower than that of adsorbed across all treatments (Table 4). This indicates that adsorbed phosphorus could partially desorb, particularly before management activities. However, after lime and compost treatment, desorption rates increased significantly. In Michit, the desorbed amounts of DAP, NPSB, and KH_2PO_4 fertilizers increased after compost and lime application. Even though, it depends on the fertilizer type (Table 4), less additional P was sorbed by the treated soils (Dou et al., 2009). A higher degree of desorption (Dr) value indicates a stronger tendency for P to desorb (Yang et al., 2019). The integrated application of lime and compost significantly increased the phosphorus desorption ratio. The increases in Dr of P in the three fertilizers are given in the table. Similarly, Sun et al., (2020) found that the phosphorus desorption ratio was different in different soils. In this study, next to DAP, the desorption ratio of KH_2PO_4 showed a significant positive response for integrated application in strong acidic soil. The desorption ratio of KH_2PO4 shows a more significant positive response to the mixed addition of the other two fertilizers in moderately acidic soil, and NPSB in the slightly acidic soil. Consistent with this study different scholars have reported that the application of lime to acidic soil increases phosphorus desorption (Mathewos et al., 2020; Sukyankij et al., 2024).

Table 4: Effect of integrated application of lime and compost on Langmuir and Freundlich desorption parameters

Site	Treatment	Langmuir equation				Freundlich equation		
		C/D =C/Dmax +1/kDmax	Dmax	K	R^2	$D = kfC^n$	R^2	Dr (%)
Michit	Ck, DAP	0.0111C+0.0193	90.09	0.58	0.9909	$517.01C^{0.345}$	0.986	6.12
	CK, NPSB	0.0097C+0.0146	103.09	0.66	0.9824	$588.302C^{0.3975}$	0.939	6.18
	CK, KH_2PO_4	0.0093C+0.0211	107.53	0.44	0.9352	$549.921C^{0.378}$	0.989	7.28
	LC, DAP	0.0005C+0.0029	2000	0.17	0.9710	$203.238C^{0.636}$	0.959	124.00
	LC, NPSB	0.0016C+0.0016	625.00	1.00	0.9979	$421.595C^{0.827}$	0.852	34.38
	LC, KH_2PO_4	0.0009C+0.0056	1111.11	0.16	0.8728	$269.774C^{0.389}$	0.831	107.77
Ufudo	Ck, DAP	0.0099C+0.0235	101.01	0.42	0.9866	$462.807C^{0.447}$	0.978	6.61
	CK, NPSB	0.0103C+0.0153	97.09	0.67	0.9985	$549.92C^{0.412}$	0.915	6.45
	CK, K_2HPO_4	0.0091C+0.0249	109.89	0.37	0.8900	$514.517C^{0.396}$	0.972	7.16
	LC, DAP	0.0013C+0.013	769.23	0.10	0.8130	$246.604C^{0.022}$	0.558	55.39
	LC, NPSB	0.0005C+0.001	2000.00	0.50	0.9063	$128.914C^{1.74}$	0.738	96.00
	LC, KH_2PO_4	0.0009C+0.0067	1111.11	0.01	0.9364	$222.331C^{0.428}$	0.867	122.22
Keyakela	Ck, DAP	0.0098C+0.0454	102.04	0.22	0.8970	$334.888C^{0.490}$	0.970	7.97
	CK, NPSB	0.0159C+0.0043	62.89	0.27	0.9945	$583.042C^{0.233}$	0.626	5.43
	CK, K_2HPO_4	0.0096C+0.0353	104.17	0.27	0.8440	$429.438C^{0.409}$	0.959	6.80
	LC, DAP	0.0017C+0.0141	588.23	0.12	0.9272	$82.319C^{0.570}$	0.603	34.94
	LC, NPSB	0.0005C+0.0018	2000.00	0.28	0.9198	$286.484C^{0.802}$	0.894	84.00
	LC, KH_2PO_4	0009C+0.0067	1111.11	0.50	0.9231	$153.144C^{0.533}$	0.788	68.33

3.6 Relationships between soil properties and P fertilizers Adsorption-adsorption parameters

The correlation analysis between selected soil chemical properties and Langmuir adsorption-desorption parameters of the different fertilizers is presented in Table 5. The pH of the soil showed a strong negative correlation with K_1, MBC, EPR, K_2 for DAP and K_L, MBC, and EPR for KH_2PO_4. Similarly, Nwoke et al., (2004) reported a significant correlation between the amount of P desorbed and pH. The organic carbon in the soil showed a strong positive correlation with Dmax of DAP and KH_2PO_4 fertilizers, whereas it was strongly negatively correlated with K_2, MBC, EPR of NPSB and MBC and EPR of KH_2PO_4. The soil organic carbon was the major factor controlling P desorption in this study (Table 5). Total nitrogen was significant and positively correlated with Dmax of DAP and KH_2PO_4. However, it was strongly and negatively correlated with K_1, MBC and EPR_2, of NPSB and MBC, and EPR of KH_2PO_4. Available phosphorus was significantly and negatively correlated with desorption bonding strength of KH_2PO_4 at $P \leq 0.05$.

Table 5: Pearson correlation of selected soil properties and Langmuir adsorption-desorption parameters

Fertilizer type	Soil properties	Parameters					
		Q_{max}	K_1	MBC	EPR	D_{max}	K_2
DAP	pH	0.22	-0.81*	-.82*	-0.82*	0.60	-0.99**
	OC	0.36	-0.65	-0.61	-0.60	0.82*	-0.83*
	TN	0.51	-0.62	-0.55	-0.60	0.83*	-0.70
	Av. P	0.58	-0.67	-0.66	-0.70	0.30	-0.65
	TP	-0.19	-0.77	-0.78	-0.80	0.10	-0.64
	PAC	0.54	-0.32	-0.32	-0.30	0.00	-0.30
NPSB	pH	0.50	-0.36	-0.52	-0.56	0.71	-0.26
	OC	0.69	-0.71	-0.82*	-0.85*	0.75	0.15
	TN	0.79	-0.86*	-0.93**	-0.95**	0.76	0.29
	Av. P	0.74	-0.49	-0.58	-0.60	0.73	-0.41
	TP	0.53	-0.45	-0.52	-0.53	0.81	-0.28
	PAC	0.47	-0.18	-0.24	-0.26	0.37	-0.48
KH_2PO_4	pH	-0.33	-.91*	-0.93**	-.92**	0.80	-0.37
	OC	-0.67	-0.75	-0.85*	-0.86*	0.97**	-0.52
	TN	-0.69	-0.70	-0.82*	-0.83*	0.98**	-0.46
	Av. P	0.15	-0.84*	-0.77	-0.79	0.69	0.69
	TP	-0.61	-0.48	-0.58	-0.57	0.61	-0.65
	PAC	0.55	-0.55	-0.42	-0.44	0.30	0.64

Note: Qmax, Dmax, K1 and K_2, MBC and EPR are adsorption, desorption maximum, bond strength, buffering, and external phosphorus requirement. Significant a code: at $P \leq 0.01$ '**' 0.01, $P \leq 0.05$ '*'

4. Conclusions

The combined application of lime and compost resulted in significant improvement in selected soil properties such as phosphorus activation coefficient, soil organic carbon, and total and available phosphorus. The phosphorus adsorption capacity of soil significantly decreased following the combined application of lime and compost in all the three soil types. Organic carbon of soil has shown a strong positive correlation with phosphorus desorption maximum. The ambiguity and difficulty in managing phosphorus requirements for plants in most agricultural systems has long been recognized, it varied from site-to-site and fertilizer to fertilizers, and it significantly decreased as a result of combined application. The external phosphorus requirement is influenced by management and type of phosphate fertilizers. In strongly acidic (Michit) soil, the desorption ratio of DAP fertilizer demonstrated a significantly superior positive response to the combined application of lime and compost compared to the remaining two fertilizers. As a recommendation, field experiments are suggested to apply the external phosphorus requirement to assess the effectiveness of fertilizers under practical conditions.

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