
Inorganic phosphorous, lime and vermicompost induced changes on phosphorus fractions and other properties of acidic Soil of Cheha district, Ethiopia

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Abstract

In acid soils, soluble inorganic phosphorus is fixed by aluminum and iron, so that phosphorous availability to plants would be inhibited. Thus, an incubation study was conducted to evaluate the effects of lime, vermicompost, and mineral P fertilizer on the distribution of P fractions, oxalate, dithionite extractable aluminum, and iron. The treatments consisted of three rates of phosphorous (0, 74.51, and 149.01 kg P ha⁻¹), three rates of vermicompost (0, 5, and 10 ton VC ha⁻¹), and four rates of lime (0, 5.70, 9.20, and 11.50 ton CaCO₃ ha⁻¹). The experiment was laid out as a complete randomized design in a factorial arrangement. The results revealed that the combined application of lime, vermicompost, and mineral P significantly ($p < 0.05$) increased labile phosphorus fractions and decreased the potential sorption capacities of the soil. As soil pH increased, exchangeable acidity and oxalate extractable Fe and Al decreased. The integrated applications of these amendments fixed aluminum and iron instead of phosphorus, thus rendering phosphorus available by keeping the inorganic phosphorus in a bioavailable, labile phosphorus pool compared to the sole application of the amendments. The combined applications of lime, vermicompost, and inorganic P to acidic soils at the Goha sampling site in Cheha district could convey an enhanced amount of available P and ensure the maintenance of higher levels of labile P. It might also contribute towards meeting crop P requirements.

Keywords: Oxyhydroxides, Soil Acidity, Inorganic Amendment, Phosphorous Fraction

Introduction

Soil acidity is the most central factor affecting plant growth and limiting crop production (Achieng et al., 2010). It is common in regions where rainfall is high enough to leach appreciable

amounts of exchangeable bases from the soil surface (Getahun et al., 2019). Particularly, it becomes a serious threat to the western and southern highlands of Ethiopia (Wassie and Boke, 2009). Phosphorus is deficient in most acid soils because soluble inorganic P is fixed by Al and Fe (Adnan et al. 2003).

In highly weathered acidic soils, the dominant species with which P readily interacts are Fe and Al oxyhydroxides (Rayment and Lyons, 2011). These oxyhydroxides create new functional groups for P adsorption (Roderigo et al., 2016) and may be found as distinct surface layers on soil particles or in complexes with the organic fraction of the soil (Sims and Pierzynski, 2005).

Soils contain inorganic P (Pi) and organic P (Po) compounds are important P sources for plants, but Po rarely represents a major portion of soil P. Information of P fraction dynamics in acidic soils is significant to evaluate P mobility in order to reduce the P retention by soils. In soils, P is found in several forms or pools, and different forms are often designated as either inorganic or organic P. Moreover, P fertilization can result in changes in soil P fractions which provide valuable facts on the impacts of P additions on soil P transformations (Lan et al., 2012). The maintenance of adequate amounts of P in the soil and maintaining the wellbeing of the soil through organic and inorganic fertilizer applications are critical for the long-term sustainability of agricultural systems. Moreover, a clearer understanding of the change in distribution and solubility of P forms in soil may provide important information for the evaluation process of P availability for plants and enhance the fertilizer management strategy (Sharply et al., 2004). For example, there is an increasing interest in the potential use of vermicompost (VC) as a soil amendment (Lordan et al., 2013).

Low soil acidity, higher oxyhydroxides of Al and Fe content, low P concentrations in the soil solution, and a higher P adsorption capacity are the characteristic features of the studied soil (Ayenew et al., 2018b). The impact of integrated application of lime, vericompost, and mineral P on the distribution of oxyhydroxides of Fe and Al, organic P, and inorganic P fractions has not yet been evaluated in the study area. Thus, for proper P fertilizer management and to overcome the low plant availability of soil P, the effects of applications of amendments on adsorption characteristics, P fraction dynamics, and related properties are required to be studied. Moreover, in spite of the existing P fixation problem in highland soils of Ethiopia, little work has been done on the dynamics of P and related properties following sole or combined applications of organic and inorganic amendments (Asmare et al., 2015). However, since available P in soil is not a

single entity, complete accounts of the P forms (organic and inorganic) present in the soils have to be appreciated in order to determine the fate of the applied P fertilizers (Fekadu et al., 2020; Dawit et al., 2002). Hence, the purpose of this study was to evaluate the effects of sole and combined applications of lime, VC, and inorganic P on the dynamics and distribution of different P fractions as well as related soil properties.

Materials and methods

Description of the study area

The study was conducted in the Cheha district of Gurage Zone in southwestern Ethiopia. The district is situated between 80 32' 0" and 80 20' 0" N, and 370 41' 20" and 380 2' 40" E, at an elevation that ranges from 900 to 2812 m asl. Ethiopian Institute of Agricultural Research (2011) classified the area into three agro-ecological zones, i.e., highlands (2300 - 3200 m asl), mid-altitude (1500 - 2300 m asl), and lowlands (500 - 1500 m asl) based on the bimodal rainfall system. The ten years mean annual rainfall of the district is about 1268 mm. The mean annual maximum and minimum temperatures were 24.97 and 10.69 0C, respectively. The dominant soil types in the study area are: Nitisols, Leptisols and Pellic Vertisols (FAO, 1988).

Site Selection, soil sampling and analysis

A preliminary soil survey and field observation was made using topographic map (1:50,000) of the study area. Soil pH (potentiometer), altitude (GPS), and slope (clinometer) were used as criteria for selection of soil sampling sites. Fifteen (15) sub-samples were collected from Goha 1 (SC1) study site to make one composite sample. Accordingly, one composite soil sample (0 - 15 cm) having pH value of less than 5.5 was obtained within an altitudinal range of 2000 - 3000 m asl and slope less than 8%. Soil pH was measured at field condition using portable pH meter. The soil samples were put in plastic bag, tagged, and transported to laboratory for analysis.

Soil P fractions and other related properties

Different forms of P were determined following the P fractions scheme as suggested by Chen et al. (2000) and Hedley et al. (1982). The oxalate extractables P, Al, and Fe (Pox, Alox and Feox) were determined in the dark with 0.05 M ammonium oxalate ((NH₄)₂C₂O₄.2H₂O, pH 3.3) (Mckeague and Day, 1966). Citrate bicarbonate dithionite-extractable Fe and Al (Fed and Ald)

were determined by the method of Mehra and Jackson (1960). The degree of P saturation (DPS) was determined as the percentage of the ratio of the different forms of P to the oxalate extractables Al and Fe (Al_{ox} and Fe_{ox}) (Van der Zee et al., 1988). The P adsorption capacity (PSC, $mmol\ kg^{-1}$) of the soil was calculated and estimated according to Börling et al. (2001).

Physicochemical properties of experimental soil

The soil group of the studied soil in the district was Nitisol (FAO, 1988), and the textural class of the studied soil was predominantly clayey (Table 1). The experimental soil was found to have the following properties.

Table 1. Selected characteristics of the experimental soil

Parameters	Soil (SC1)
Soil group	Nitisol
Sand (%)	23.2
Silt (%)	28.6
Clay (%)	48.2
Bulk density ($g\ cm^{-3}$)	1.32
Field capacity (%)	29.5
Permanent wilting point (%)	19.6
pH (H_2O)	4.65
Cation exchange capacity ($cmol_c\ kg^{-1}$)	21.15
Exchangeable acidity ($cmol_c\ kg^{-1}$)	3.76
Exchangeable Al ($cmol_c\ kg^{-1}$)	2.54
Organic carbon (%)	1.58
Mehlich-III P ($mg\ kg^{-1}$)	8.09
Al_{ox} ($mmol\ kg^{-1}$)	147.37
Fe_{ox} ($mmol\ kg^{-1}$)	174.69
Phosphorous sorption Capacity (PSC) ($mg\ P\ Kg^{-1}$)	133.54

Source: Ayenew et al. 2018a

Analysis of the composition of vermicompost and lime

Parthenium hysterophorus, wheat straw, cow dung and poultry manure, were used as substrates in preparing the vermicompost. The vermicompost that has been harvested after sixty days of

decomposition was dark brown in color. Consequently the pH, OC, C:N, and total concentrations of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) in the vermicompost were determined. The total nutrient contents of vermicompost were measured in suspensions obtained after dry ashing at 500°C, followed by cooling to room temperature in muffle furnace, slowly removal of ashed samples and dissolving with 1N HCl and diluted to 50 ml volume. Each element was analyzed based on standard laboratory procedure suggested by Gavlak *et al.* (2005). The vermicompost prepared had a pH value of 8, verifying it could be used for liming the soil and was analyzed for its nutrients concentrations. It was also found to have a C: N of 10.12, and 24.40% OC. Further analysis of this amendment showed that its total N, P, K, Na, Ca, Mg content was found to be 2.41, 109.23, 577.54, 133.92, 1198.28, 137.20 mgkg⁻¹ respectively.

Incubation experiment

The composited soil sample (0-15cm) was air dried, ground, and passed through a 2 mm sieve, and then 300 g soil was placed in a plastic pot in the green house for the next step. Three rates of lime were set, of which two of them, 9.20 and 11.50 tons CaCO₃ ha⁻¹ were separately applied to get target pH values of 6.0, 6.5 and the third one was 5.70 tons CaCO₃ ha⁻¹ which is half of the lime required to bring a pH value of 6.5. The lime used for this particular study had a CCE of 96.15%. Hence, the real field application rates of lime were 0, 5.93, 9.57, and 11.96 tons lime ha⁻¹ for the soil. Vermicompost (<0.25mm sieve) with 0, 5, and 10 tons ha⁻¹ rates and inorganic P at rates of 0, 74.51 and 149.01 kg P ha⁻¹ were prepared for incubation. Accordingly, the respective integrated or separate amendments were thoroughly mixed with a given amount (300 g) of soil and homogenised. A factorial combination of vermicompost (0, 5 and 10 tons ha⁻¹ soil), lime (0, 5.93, 9.57 and 11.96 tons ha⁻¹ soil), and inorganic P (0, 152.2 and 304.38 kg P₂O₅ ha⁻¹ soil) was executed to find out the interaction effects of the treatments in charge. The experiment was laid out in a completely randomised design (CRD) with three replications. Consequently, to the three hundred grams of surface (0-15 cm) air-dried soil (< 2 mm), the specified amounts of lime, vermicompost (< 0.25 mm) and solid triple superphosphate (TSP) (sieved <1 mm) were applied jointly or separately. The amended soils were then mixed thoroughly, moistened to field capacity, and incubated for 60 days. After the incubation trail was completed, the soil sample from each pot should be collected and analysed for CEC, TN,

available phosphorous, exchangeable acidity, pH, oxalate extractable Al and Fe and different fractions of phosphorous.

Statistical analysis

Statistical analysis of the data, including Pearson's simple correlation coefficient and analysis of variance (ANOVA), was executed using Statistical Analysis System (SAS) version 9.1 (SAS Institute, 2004).

Results and discussion

pH, exchangeable acidity, CEC and available P after incubation

The interaction of the three factors significantly influenced the pH of the soil (Table 3). The highest pH value (6.73) of the soil was recorded from the joint application of lime, vermicompost, and inorganic phosphorus in a proportion of 11.96 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹ and 149.01 kg P ha⁻¹ respectively, whilst the lowest pH value (4.68) was achieved by the application of P alone at all levels. The findings of the present study were in line with the work of Ashoka et al. (2014), who reported that the addition of inorganic P alone did not have any appreciable effect on soil pH values.

The acidity reduced by the integrated application of lime, vermicompost, and inorganic P was synergistic, having a mechanism where calcium from lime replaces the exchangeable forms of Al and Fe, which react with hydroxide ions released from water in the soil solution to form insoluble Al and Fe hydroxides (Buni, 2015), while compost forms an insoluble Al and Fe organic acid complex bound to the exchangeable Al and Fe (Haynes and Mokolobate, 2001). In the meantime, the adsorption of the added phosphate at the exchange site might have contributed to the rise in pH of the studied soil through ligand exchange.

The highest (21.89 mg kg⁻¹) value of Mehlich-III P was recorded when vermicompost was applied in combination with lime and inorganic P at the rates of 10 ton VC ha⁻¹, 9.20 ton CaCO₃ ha⁻¹ and 149.01 kg P ha⁻¹, while the lowest (8.77 mg kg⁻¹) value was recorded from the control. The compelling reason for the enhanced increase in available P in soils after incubation could be due to the ability of the lower molecular organic acids and their anionic carboxylate functional groups to interact with soil by occupying P adsorption sites and competing with phosphate (Guppy et al., 2005). The increased amount of phosphate adsorbed on free metal oxyhydroxides

and the presence of soluble cations in lime and vermicompost, which displace acidic cations, might have triggered the availability of P. In harmony with this, Kamprath (1984) reported that the Ca^{2+} in lime and the Ca^{2+} , K^{+} , and Na^{+} in vermicompost could displace Al^{3+} , Fe^{2+} and H^{+} ions from the soil sorption sites, so that P fixation would be reduced.

The increase in soil pH was reflected by a corresponding decrease in exchangeable acidity from 2.57 cmolc kg^{-1} in control to 0.31 cmolc kg^{-1} ($P < 0.01$). The interaction of the three factors significantly altered the levels of exchangeable acidity in the studied soil (Table 3). The greatest (44.65%) change was obtained from the integrated applications of lime, vermicompost and inorganic P at rates of 11.96 ton ha^{-1} , 10 ton VC ha^{-1} , 149.01 kg P ha^{-1}), while the lowest (0.65%) was recorded from the controlled soil. The reduction in exchangeable acidity might partly be attributed to an initial increase in soil pH that was observed with lime and vermicompost.

It could also be noted that the interaction of the three factors appeared to have a significant effect and decreased the exchangeable Al of the soil by 31.65 to 91.75% compared to the control, indicating the synergistic effects of the three factors. An increase in soil pH might have resulted in the precipitation of exchangeable and soluble Al as insoluble Al hydroxides (Ritchie 1994), thus reducing the concentration of Al in the soil solution. However, there are other mechanisms involved in the reactions of Al with OM that are intricate and probably involve complex formation with low-molecular-weight organic acids, such as citric, oxalic, and malic acids, and humic material produced during the decomposition of the OM and the adsorption of Al onto the decomposing organic residues (Ritchie, 1994). In agreement with this result, Teshome et al. (2017) reported that the integrated application of lime, mineral P, and compost had reduced the exchangeable aluminum due to the formation of organo-Al (chelation) complexes, insoluble aluminum hydroxide precipitate, and aluminum phosphate precipitate from compost, lime, and inorganic P.

Table 3. Effects of amendments on selected chemical properties of soil (SC1)

Treatments		pH	exAc(cmol _c kg ⁻¹)	exAl	CEC	Mehlich 3 P (mg/kg)...	PAcs (%)	PAIs		
P0	V0	L0	4.68v	2.57a	1.37a	22.05op	8.77r	11.76a	6.27a	
		L1	5.67o	0.59i	0.11i	22.15op	9.06rq	2.70i	0.49i	
		L2	5.93k	0.42k	0.11i	22.33on	9.43q	1.89k	0.48i	
	L3	6.33f	0.37m	0.11i	22.48n	10.09p	1.70m	0.48i		
		V1	L0	4.79u	2.15b	0.33b	23.42m	9.39q	9.85b	1.49b
			L1	5.85m	0.68h	0.03j	25.39g	12.18n	3.11h	0.12j
	L2		6.03i	0.59i	0.11i	25.83def	12.10n	2.70i	0.48i	
	L3	6.67bc	0.33o	0.11i	28.71b	12.73m	1.51o	0.48i		
		V2	L0	4.99t	1.99c	0.31cd	24.02jkl	10.36po	9.14c	1.41cd
			L1	5.94k	0.59i	0.03j	25.60gf	10.75o	2.70i	0.12j
	L2		6.11h	0.42k	0.11i	25.93cde	12.59m	1.89k	0.48i	
	P1	L3	6.71ba	0.35n	0.03j	29.45a	13.17l	1.59n	0.12j	
V0			L0	4.68v	2.56a	0.32bc	23.08p	16.73k	11.71a	1.44bc
			L1	5.68o	0.68h	0.11i	23.79l	16.86k	3.11h	0.48i
		L2	5.76n	0.50j	0.11i	24.16j	17.95i	2.31j	0.48i	
L3		6.32f	0.39l	0.11i	24.46hi	18.28ih	1.79l	0.48i		
		V1	L0	5.18s	1.82d	0.29e	23.44m	16.99kj	8.34d	1.35e
			L1	5.95jk	0.50j	0.03j	25.40g	17.36j	2.31j	0.12j
L2			6.02i	0.35n	0.11i	25.84c-f	18.09ih	1.59n	0.48i	
L3		6.66c	0.33o	0.11i	28.73b	18.41h	1.49o	0.48i		
		V2	L0	4.99t	1.56f	0.27f	24.07jk	18.26ih	7.13f	1.21f
			L1	5.99ji	0.42k	0.11i	25.64fg	19.37feg	1.89k	0.48i
L2			6.29f	0.59i	0.11i	25.99cd	19.30fg	2.70i	0.48i	
L3	6.68abc	0.34no	0.11i	29.48a	19.41fe	1.56no	0.48i			
	P2	V0	L0	4.68v	2.54a	0.31cde	22.12op	18.99g	11.76a	1.40cde
			L1	5.36q	0.42k	0.11i	23.84kl	19.13fg	1.89k	0.48i

	L2	5.86lm	0.42k	0.19h	24.19ij	20.54dc	1.89k	0.85h
	L3	6.39e	0.33o	0.03j	24.52h	20.73c	1.49o	0.12j
V1	L0	5.19s	1.74e	0.29de	23.45m	19.35fg	7.93e	1.37de
	L1	5.55p	0.50j	0.11i	25.42g	19.06fg	2.30j	0.48i
	L2	5.94k	0.59i	0.11i	25.87c-f	19.77e	2.70i	0.48i
	L3	6.55d	0.35n	0.11i	28.76b	20.17d	1.60n	0.48i
V2	L0	5.24r	1.47g	0.25g	24.11jk	21.37b	6.73g	1.15g
	L1	5.91kl	0.59i	0.19h	25.66efg	21.62ba	2.70i	0.85h
	L2	6.24g	0.42k	0.11i	26.12c	21.89a	1.89k	0.48i
	L3	6.73a	0.31p	0.03j	29.53a	21.82a	1.43p	0.12j
Mean		5.82	0.86	0.17	25.11	16.45	3.91	0.79
F-test		**	**	**	**	**	**	**
CV(%)		4.49	1.05	4.49	0.68	1.47	1.05	4.49

Means followed by the same letter within a column are not significantly different; ** = significant at $P \leq 0.01$ using the Duncan's multiple range test; CV = coefficient of variation of treatments; exAc = exchangeable acidity; exAl = exchangeable Al; PAcs = percentage of acid saturation; PAls = percentage of Al saturation; L0 = No lime; L1 = 5.93 tons lime ha⁻¹; L2 = 9.57 tons lime ha⁻¹; L3 = 11.96 tons lime ha⁻¹; V0 = No vermicompost; V1 = 5 tons vermicompost ha⁻¹; V2= 10 tons vermicompost ha⁻¹; P0 = No mineral P; P1 = 74.51 kg P ha⁻¹; P2= 149.01 kg P ha⁻¹.

Amendments effect on Oxalate and Dithionite extractable P, Al and Fe

Data revealing the distribution of extractable P, Fe and Al after eight weeks of incubation in the soil are presented in Tables 4; Since the oxalate and dithionite extractable iron and aluminum contents of the soil were high (Ayenew et al., 2018a), Fe and Al oxyhydroxides could be the dominant species with which P interacts. Thus, the changes in some of the properties of soil upon applications of amendments might be ascribed to the change in concentration of the extractable form of Fe and Al present in the soil (Table 4). As a case in point, Torrent et al. (1990) reported that the nature, amount, and distribution of iron and aluminum oxides in soil affect the ionic charge, chemical characteristics, and ion adsorption, especially phosphorous sorption.

The interaction effects showed a significant ($p < 0.01$) effect on oxalate-extractable aluminum (Alox) (Table 4). The least (141.93 mmol kg⁻¹) was recorded from the integrated applications of lime, vermicompost, and inorganic P. Thus, the highest (3.69%) reduction in oxalate extractable Al was obtained by the combined applications of lime, vermicompost, and inorganic P at the rates of 9.57 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹ and 149.01 kg P ha⁻¹ (Table 4). In the interim, integrated applications of amendments had a significant ($p < 0.01$) influence on dithionite citrate bicarbonate extractable aluminum (Ald). Consequently, the highest (173.77 mmol kg⁻¹) dithionite citrate bicarbonate extractable (Ald) value was obtained from the control, while the lowest (169.23 mmol kg⁻¹) attained from pooled applications of lime, vermicompost, and inorganic P at the rates of 9.20 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹ and 149.01 kg P ha⁻¹ (Table 4).

A significant ($p < 0.01$) decrease in oxalate (Feox) and dithionite extractable iron (Fed) were observed as a result of the integrated applications of lime, vermicompost, and inorganic P. The values of Feox obtained after incubation ranged from 88.59 - 96.39 mmol kg⁻¹. However, the least (88.59 mmol kg⁻¹) was recorded from the integrated applications of lime, vermicompost, and inorganic P at the highest rates (11.96 ton lime ha⁻¹, 10 ton VC ha⁻¹, 149.01 kg P ha⁻¹). It has been reported that in Fe- and Al-rich soil, organic matter could inhibit the crystallisation of Al and Fe by forming stable complexes with them, which in turn could increase P sorption as non-crystalline Al and Fe increased (Kang et al., 2009). Accordingly, the largest (49.29%) reduction in Feox at the exchange sites was recorded from integrated applications of lime, vermicompost, and inorganic P at rates of 11.96 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹, and 149.01 kg P ha⁻¹ respectively, while the least (46.02%) was obtained from the sole application of vermicompost at rates of 10 ton ha⁻¹.

It could be noted that the synergistic effects of the three factors on the oxalate and dithionite extractable Fe and Al were remarkable ($p < 0.01$). This might have occurred through different reaction mechanisms like the liming effect, which develops negative charge through abstraction of H^+ by OH^- ions and Ca^{+2} ions displacement of Al at the exchange sites, forming insoluble precipitates $Al(OH)_3$. Additionally, formations of organo-metal complexes from soluble organic molecules that arouse from organic amendments could in turn occupy the exchange sites and inhibit the interaction between the metallic oxyhydroxides and oxalate extractants. Furthermore, through the adsorption reaction through which soil interacts with the applied inorganic P, the amount of phosphate adsorbed on metal oxyhydroxides could be increased. In this regard, the results of the present study were concomitant with those of Asmare et al. (2015), in which the reductions in A_{ox} , F_{ox} , A_{d} and F_{d} contents were reported and justified by the fixation of Al and Fe in the form of Al-P and Fe-P.

In the current study, the integrated applications of the three factors (lime x vermicompost, x inorganic P) to soil showed a significant ($p < 0.01$) difference in the amount of oxalate extractable P (P_{ox}). The combined application of the amendments at rates of 11.96 ton $CaCO_3$ ha⁻¹, 10 ton VC ha⁻¹ and 149.01 kg P ha⁻¹ resulted in the highest (8.70 mmol kg⁻¹) P_{ox} , whereas the lowest (5.88 mmol kg⁻¹) was recorded from the control. It can be observed that as the amount of oxalate and dithionite extractable forms of those metal oxides is reduced from the exchange sites, the amount of ammonium oxalate-extracted phosphorous (P_{ox}) could be enhanced. Similar to the present study, it has been noted that sole or integrated applications of P sources (organic and inorganic) had a significant effect on the oxalate extractable Al and Fe (Gikonyo et al., 2011), which in turn influence P_{ox} , since P adsorbed by soil is mainly attributed to P adsorbed on amorphous metal oxides (F_{ox} and A_{ox}) (Cui et al., 2017).

Phosphorous sorption capacities were significantly ($P < 0.01$) influenced by the integrated applications of lime, vermicompost, and inorganic P (Table 4). After the incubation period, the highest sorption capacity was recorded from the soil incubated solely with vermicompost at the rate of 10 ton ha⁻¹ (132.98 mmol kg⁻¹) and the lowest (123.31 mmol kg⁻¹) value was obtained from the combined applications of the treatments at the rates of 9.57 ton $CaCO_3$ ha⁻¹, 10 ton VC ha⁻¹, and 149.01 kg P ha⁻¹. The highest sorption capacity recorded from the sole application of vermicompost might be attributed to the formation of stable complexes. In Fe and Al rich soil, organic matter could inhibit the crystallization of Al and Fe by forming stable complexes with

them, which in turn can increase P sorption as non-crystalline Al and Fe increase (Kang et al. 2009). It can also be seen that the adsorption capacity of the soil decreased significantly with increased application rates of integrated amendments. The reduction in magnitude of phosphorous sorption capacities due to integrated application could be attributed to the coating of metal oxyhydroxide species by organic molecules from vermicompost applications, which reduce the availability of binding sites for phosphate ions; formations of insoluble aluminum hydroxides from the applications of lime, which reduce adsorptions of phosphate on the exchange site; and the addition of inorganic P, which occupy the exchange sites. Thus, the result of the present study is similar to that of the study by Gikonyo et al. (2011), which showed that integrated applications of P sources had a significant effect on the PSC of a soil.

The DPS (%) value was significantly ($P < 0.01$) affected by the combined applications of lime, vermicompost, and inorganic P (Table 4). The maximum DPS (7.06%) value was recorded from the integrated applications of the amendments at the rates of 11.50 ton $\text{CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} , and 149.01 kg P ha^{-1} , where the minimum DPS (4.49%) value was observed in the control. The result of the present study is in line with the study made by Gikonyo et al. (2011), which showed that integrated applications of P sources had a significant increasing effect on the DPS of the soils. It can be inferred that the observed increase in the DPS of the soils might have brought about the better mobility of P in the soils. In this regard, Yan et al. (2017) reported that due to the decrease of the sorption sites for further P sorption, the concentrations of exchangeable P increased with increasing DPS.

On the other hand, since phosphate ions are negatively charged, continued P fixation leads to a "semi-permanent" increase in surface negative charge, resulting in a decrease in the electric potential of the reacting soil particle (Celi et al., 2000). Consequently, increasing P saturation leads to weaker and weaker retention of P, implying that the degree of phosphorus saturation (DPS) appears to govern solution P concentration (Magdoff et al., 1999).

Table 4. Effects of amendments on Oxalate and dithionite extractable iron, Aluminum and phosphorous of SC1 Soil

Treatments		Al _{ox}	Al _d	Fe _{ox}	Fe _d	P _{ox}	PSC	DPS	
		mmolkg ⁻¹						%	
P0	V0	L0	150.35a	173.77a	94.29a	634.82a	5.88r	130.64a	4.49n
		L1	147.16b	171.60b	92.53b	630.72b	6.62q	127.99b	5.17m
		L2	145.94b-g	171.51b	92.37bc	630.33b	6.74qp	127.26b-e	5.29lm
		L3	144.44h-k	170.65b-f	92.29bcd	629.02c	6.88op	126.41c-h	5.44kl
	V1	L0	151.59ab	171.43b	95.89ab	628.38cd	6.74qp	132.15a	5.09r
		L1	146.84bc	171.37bc	91.79b-f	627.99cde	6.75qp	127.43bcd	5.29lm
		L2	146.35b-e	171.23bcd	91.69b-f	627.63def	7.15lm	127.11b-e	5.63ij
		L3	144.91f-j	171.13bcd	91.61b-f	627.51def	7.17lkm	126.30d-i	5.68hi
	V2	L0	152.64a	171.35bcd	96.39a	626.79efg	6.79op	132.98a	5.11qr
		L1	145.33d-h	171.29bcd	91.27b-h	626.65e-h	6.83op	126.35d-i	5.41kl
		L2	144.63h-k	171.20bcd	91.08b-i	626.61e-i	7.54hi	125.87f-k	5.99ef
		L3	144.48h-k	171.03bcd	90.75c-i	626.49f-j	7.62hg	125.62g-k	6.07ef
P1	V0	L0	147.12b	171.57b	90.99b-i	630.76b	6.91on	127.15b-e	5.44kl
		L1	142.84l-o	171.45b	90.87c-i	628.58cd	6.85op	124.80jkl	5.49jk
		L2	143.14l-o	171.03bcd	90.69d-j	627.71c-f	7.68g	124.87jkl	6.150e
		L3	142.87l-o	170.98b-e	90.59e-j	627.67c-f	7.06nm	124.67kl	5.66hi
	V1	L0	146.47bcd	171.14bcd	91.19b-i	625.92g-k	7.18lkm	126.91b-f	5.66hi
		L1	146.04b-f	170.79b-f	90.96b-i	625.89g-k	7.31jk	126.56c-g	5.78ghi
		L2	143.92i-l	170.69b-f	90.66d-j	625.83g-k	8.11e	125.26h-l	6.47cd
		L3	145.67c-h	170.52b-g	90.52e-k	625.63g-k	8.27d	126.13e-i	6.56c

P2	V2	L0	145.12e-h	170.47b-g	90.19f-l	625.25h-l	7.43ji	125.65g-k	5.91fg
		L1	143.57k-n	170.44b-g	90.14f-l	625.13jkl	7.58hg	124.80jkl	6.07ef
		L2	145.39d-h	170.21b-g	90.03g-l	625.03jkl	8.53bc	125.72g-k	6.79b
	V0	L3	142.99l-o	169.95c-g	89.79h-l	624.61klm	8.61bac	124.31lm	6.93ab
		L0	145.18e-i	171.25bcd	90.29e-k	625.25h-l	7.65hg	125.74g-k	6.08e
		L1	143.64j-m	170.86b-f	90.26e-k	625.21h-l	7.27lk	124.89jkl	5.82gh
	V1	L2	142.28no	170.83b-f	90.25e-l	625.16i-l	7.87f	124.17lm	6.34d
		L3	142.18o	170.75b-f	90.23e-l	625.08jkl	8.48c	124.11lm	6.83b
		L0	145.97b-g	170.73b-f	91.11b-i	625.91g-k	8.28d	126.60c-g	6.54c
	V2	L1	144.45h-k	170.50b-g	90.83c-i	625.85g-k	7.68hg	125.64g-k	6.11e
		L2	144.81f-k	170.47b-g	90.62e-k	625.79g-k	8.25ed	125.72g-k	6.56c
		L3	143.11l-o	170.42b-g	90.52e-k	625.62g-k	8.65ba	124.76jkl	6.93ab
		L0	144.88f-j	169.94d-g	89.57i-l	623.99mn	8.64ba	125.19i-l	6.90ab
		L1	144.74g-k	169.53fg	89.08jkl	623.55mno	8.21ed	124.86jkl	6.57c
		L2	141.93o	169.23g	88.99kl	622.82no	8.67ba	123.31m	7.03a
	L3	142.37mno	169.59efg	88.59l	622.65o	8.70a	123.33m	7.06a	
Mean		144.95	170.86	91.08	626.61	7.57	126.04	6.01	
F-test		***	***	***	***	***	***	***	
CV		0.74	0.41	1.12	0.12	1.17	0.72	1.83	

Means followed by the same letter within a column are not significantly different; ** = significant at $P \leq 0.01$ using the Duncan's multiple range test; CV = coefficient of variation of treatments; Al_{ox} = oxalate extractable Aluminum; Al_d = dithionite extractable Aluminum; Fe_{ox} = oxalate extractable iron; Fe_d = dithionite extractable iron; P_{ox} = oxalate extractable phosphorous; PSC = phosphorous sorption capacity; DPS = degree of phosphorous saturation; L0 = No lime; L1 = 5.93 tons lime ha^{-1} ; L2 = 9.57 tons lime ha^{-1} ; L3 = 11.96 tons lime ha^{-1} ; V0 = No vermicompost; V1 = 5 tons vermicompost ha^{-1} ; V2= 10 tons vermicompost ha^{-1} ; P0 = No mineral P; P1 = 74.51 kg P ha^{-1} ; P2= 149.01 kg P ha^{-1} .

Amendments effect on forms of Phosphorous

Results of the analysis of variance indicated that the integrated applications of the three factor amendments had a significant ($P < 0.01$) effect on the amounts and distributions of $\text{NH}_4\text{Cl-P}$, $\text{NaHCO}_3\text{-Pi}$, $\text{NaOH-Pi}_{\text{sn}}$, HCl-Pi , and NaOH-Pi fractions in the soil (Table 5). After an eight-week incubation period, the distributions and forms of Pi were in the order of $\text{NH}_4\text{Cl-P} < \text{NaHCO}_3\text{-Pi} < (\text{NaOH-Pi})_{\text{sn}} < \text{HCl-Pi} < \text{NaOH-Pi}$. The highest percentage change in each fraction was recorded from the interactions of three factors, whereas the lowest was obtained from the control.

The NaOH-Pi was the largest extractable inorganic P fraction, contributing to about 22.66 – 45.49% and 17.76 – 42.07% of the total P in the studied soil. Thus, NaOH-P was the major sink for the applied P. Previous studies also reported that organic amendments with high P contents could significantly increase NaOH-Pi contents (Li et al., 2015). Similar results have been reported by Pavan and Andmcioli (1995), where application of compost was able to promote NaOH-Pi . It can be inferred that since the NaOH-Pi fraction is a site for P sorption; an increase in this fraction provides evidence that P-rich amendments might decrease future P sorption in soil by reacting with these sorption sites (Yan et al., 2013).

After eight weeks of incubation, the least (2.04 mg kg⁻¹) concentration of the readily available NH_4Cl extractable P was recorded in the control, and the highest (33.37 mg kg⁻¹) was obtained from the combined applications of lime, vermicompost, and inorganic P at rates of 11.96 ton CaCO_3 ha⁻¹, 10 ton VC ha⁻¹, 149.01 kg P ha⁻¹ respectively. On the other hand, integrated applications of the amendments tended to affect HCl-Pi significantly (Table 5). The highest value of HCl-Pi was recorded from the interaction of lime, vermicompost, and inorganic P, at their respective maximum rates (11.50 ton CaCO_3 ha⁻¹, 10 ton VC ha⁻¹, and 149.01 kg P ha⁻¹), whereas the lowest was recorded from the control. The two labile P fractions ($\text{NH}_4\text{Cl-P}$, $\text{NaHCO}_3\text{-Pi}$) varied considerably ($p < 0.01$) when the combined applications of lime, vermicompost, and inorganic P were executed. While the lower plant-available chemisorbed Pi associated with amorphous and crystalline Fe and Al hydroxides and clay minerals (NaOH-pi) and moderately labile, easily mineralisable ($\text{NaHCO}_3\text{-Po}$) and less labile (NaOH-Po) were significantly altered during the incubation period.

Table 5. Effects of amendments on inorganic and organic P fractions of SC1 soil

Treatment (kg ha ⁻¹)			NH ₄ Cl-pi	NaHCO ₃ -pi	NaHCO ₃ -po	NaOH-pi	NaOH-po	NaOH-pi) sn	NaOH-po) sn	HCl-pi
		mg kg ⁻¹							
P0	V0	L0	2.04r	2.46z	2.79z	142.35j	153.85i	34.09ef	36.27klm	65.53hi
		L1	2.15r	2.49	2.79z	142.24j	153.81i	33.68f	35.96lm	65.76hi
		L2	2.21r	2.59y	2.79z	142.10j	153.72i	33.68f	35.86m	65.96ghi
		L3	2.16r	2.75x	2.79z	141.83j	153.47i	34.06ef	36.01lm	66.17ghi
	V1	L0	2.64q	2.59y	3.21t	146.06i	166.33h	35.31def	39.45j	65.96ghi
		L1	4.76o	6.72w	3.25s	146.57i	165.87h	35.14def	39.18jk	69.35ghi
		L2	4.77o	6.90v	3.29q	156.46h	165.74h	35.56def	38.76j-m	74.04d
		L3	4.82o	7.07u	3.45ij	156.40h	165.41h	35.62def	38.84jkl	82.91c
	V2	L0	3.23p	2.73x	3.27r	171.19g	170.61g	36.66de	43.78i	68.08ghi
		L1	5.36n	6.91v	3.40l	171.54g	170.24g	36.25def	43.29i	73.65de
		L2	5.37n	7.08u	3.44j	171.26g	170.01g	36.17def	43.66i	86.48bc
		L3	5.41n	7.28t	3.47g	171.65g	169.97g	36.77d	43.54i	97.04a
P1	V0	L0	14.71m	7.87s	3.10y	395.58f	182.73f	53.22c	81.24e	64.8i
		L1	16.80l	10.62p	3.12wx	395.15f	182.50f	53.61c	78.19f	65.93ghi
		L2	16.84l	10.79o	3.14v	395.28f	182.29f	53.48c	78.55ef	65.10i
		L3	16.89l	10.99n	3.18u	395.36f	182.17f	52.99c	78.47ef	66.30ghi
	V1	L0	17.32k	8.19q	3.31p	400.66e	233.43c	55.52bc	53.61h	65.67hi
		L1	19.45i	14.97h	3.32o	400.17e	233.37c	55.29bc	53.43h	72.64def
		L2	19.46i	15.09g	3.33n	400.46e	233.23c	55.55bc	53.57h	84.58bc
		L3	19.50i	15.25f	3.37m	400.08e	233.01c	55.39bc	52.73h	95.64a
	V2	L0	17.92j	8.11r	4.34f	527.87c	228.14d	57.29b	58.57g	68.16ghi
		L1	20.04h	15.10g	4.39e	527.24c	228.00d	57.73b	58.25g	73.87de
		L2	20.05h	15.26f	4.39e	527.39c	227.78d	57.41b	58.37g	86.79bc
		L3	20.09h	15.46e	4.39e	527.70c	227.70d	57.59b	58.58g	97.35a
P2	V1	L0	27.84g	11.85m	3.12xy	471.75d	215.86e	69.28a	101.99b	65.79hi
		L1	29.24f	14.57j	3.13vwx	471.36d	215.79e	69.13a	102.11b	69.96efg
		L2	29.98e	14.74i	3.13vw	471.16d	215.42e	69.62a	102.30b	75.03d
		L3	30.03e	14.92h	3.13v	471.13d	215.39e	69.50a	102.44b	86.91bc
	V1	L0	30.46d	12.25k	3.42k	601.62b	278.81b	69.41a	118.36a	65.88h

	L1	32.58b	18.95d	3.45ij	601.20b	278.65b	69.47a	118.83a	72.85def
	L2	32.59b	18.96d	3.46hi	601.11b	278.59b	69.46a	118.44a	84.79bc
	L3	32.64b	19.29b	3.46gh	601.29b	278.24b	69.57a	118.55a	95.85a
V2	L0	31.05c	12.05l	4.44d	628.42a	373.69a	70.26a	81.35e	68.39ghi
	L1	33.17a	18.98d	4.50c	628.02a	373.55a	70.47a	91.17d	74.09d
	L2	33.19a	19.11c	4.54b	628.06a	373.34a	70.48a	93.52cd	87.03b
	L3	33.37a	19.44a	4.58a	627.13a	373.29a	70.23a	96.19c	97.58a
Mean		17.78	11.12	3.49	387.63	222.34	53.47	68.98	75.89
F-test		**	**	**	**	**	**	**	**
CV%		1.46	0.39	0.21	0.42	0.74	3.07	2.65	3.26

Means followed by the same letter within a column are not significantly different; ** = significant at $P \leq 0.01$ using the Duncan's multiple range test; CV = coefficient of variation of treatments; $\text{NH}_4\text{Cl-pi}$ = ammonium chloride extractable P; $\text{NaHCO}_3\text{-pi}$ = sodium bicarbonate extractable inorganic P; $\text{NaHCO}_3\text{-po}$ = sodium bicarbonate extractable organic P; NaOH-pi = sodium hydroxide extractable inorganic P; NaOH-po = sodium hydroxide extractable organic P; NaOH-pi)sn = sonicated sodium hydroxide extractable inorganic P; NaOH-po)sn = sonicated sodium hydroxide extractable inorganic P; HCl-pi = hydrochloric acid extractable inorganic P; L0 = No lime; L1 = 5.93 tons lime ha^{-1} ; L2 = 9.57 tons lime ha^{-1} ; L3 = 11.96 tons lime ha^{-1} ; V0 = No vermicompost; V1 = 5 tons vermicompost ha^{-1} ; V2 = 10 tons vermicompost ha^{-1} ; P0 = No mineral P; P1 = 74.51 kg P ha^{-1} ; P2 = 149.01 kg P ha^{-1} .

Correlation among soil properties

The readily available NH₄Cl extractable P was strongly positively correlated with Mehlich 3-P, NaHCO₃-Pi, NaHCO₃-Po, HCl-P, NaOH-Pi, NaOH-Po and Pox (Table 6). This could be an indication of the presence of higher concentrations of NH₄Cl extractable P in soils where there were prominently higher concentrations of Mehlich 3-P, NaHCO₃-Pi, NaHCO₃-Po, HCl-P, NaOH-Pi, NaOH-Po and Pox in the soil. The correlation result verified the scientific speculation that Pox thought to be initially adsorbed with P and that the higher the concentrations of native P, the smaller the size of the adsorption sites left over for P added in the form of amendments. The rationale for the strong positive association between HCl-P and readily available P might be the occurrence of dissolution and not precipitation in acidic soils.

Readily available fractions of P (NH₄Cl-P, NaHCO₃-Pi and NaHCO₃-Po) in the studied soil had strong and negative associations with oxalate extractable Fe (Fe_{ox}), oxalate extractable Al (Al_{ox}) and PSC. The results pointed out that the availability of P was very low in soils dominated by higher concentrations of free oxyhydroxides of Fe and Al. In addition, NaOH-Pi and NaOH-Po were strongly and negatively correlated with Fe_{ox}, Al_{ox} and PSC.

Table 6. Correlation matrix obtained from soil properties in SC1 sampling site

	M-3	NH ₄ Cl-P	NaHCO ₃ -Pi	NaHCO ₃ -Po	NaOH-pi	NaOH-po	HCl-p	Al _{ox}	Fe _{ox}	P _{ox}	PSC
pH	0.19	0.09ns	0.38*	0.26ns	0.07ns	0.13ns	0.75**	-0.54**	-0.27*	0.46*	-0.48*
M-3		0.94**	0.91**	0.59**	0.95**	0.78**	0.35*	-0.61**	-0.69**	0.82**	-0.73**
NH ₄ Cl-P			0.91**	0.49*	0.96**	0.83**	0.29*	-0.54*	-0.61**	0.79**	-0.64**
NaHCO ₃ -Pi				0.56*	0.88**	0.77**	0.53*	-0.59**	-0.63**	0.82**	-0.69**
NaHCO ₃ -Po					0.64**	0.73**	0.44**	-0.35*	-0.59**	0.66**	-0.51*
NaOH-pi						0.85**	0.27*	-0.49**	-0.63**	0.79**	-0.62**
NaOH-po							0.33*	-0.37*	-0.60**	0.77**	-0.53*
HCl-p								-0.39*	-0.39*	0.66**	-0.44*
Al _{ox}									0.56**	-0.60**	0.92**
Fe _{ox}										-0.69**	0.84**
P _{ox}											-0.72**

ns = non-significant* and ** = significant at 0.05 and 0.01 probability levels, respectively; M-3=Mehlich 3, PSC= phosphorous sorption capacity, P_{ox}= oxalate extractable p, Al_{ox} = oxlate extractable Al, Fe_{ox} = oxalate extractable Fe, and NH₄Cl-P, NaHCO₃-pi, , NaOH-pi,= NH₄Cl, NaHCO₃ and NaOH extractable inorganic P respectively; NaHCO₃-Po, NaOH-Po = NaHCO₃, NaOH extractable organically bound P respectively, HCl-P = HCl extractable P

Conclusions

The combined application of lime, vermicompost, and inorganic P is effective in reducing exchangeable acidity and exchangeable aluminum in the study area. This combined application of lime, vermicompost, and inorganic P had also brought higher and better available P. Oxalate and dithionite citrate bicarbonate extractable Fe and Al, which show the potential adsorption capacity of soils, could be reduced significantly by the combined use of the treatments. The present study showed that the combined applications of lime, vermicompost, and inorganic P to acidic soils in Goha-1 in Cheha district could enhance the amount of available P and improve the problem of acidity and P deficiency. It can also ensure the maintenance of higher levels of labile P in the soil and have a highly significant influence on those soil properties as well. It can be concluded that integrated applications of lime, vermicompost, and inorganic P could contribute towards meeting crop P requirements. Therefore, the smallholder farmers and stakeholders in the study area should carry out integrated applications of lime, vermicompost, and inorganic P and start technologies like low input P management strategies to ease phosphorous and acidity-related problems.

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