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

Background: In acid soils, soluble inorganic phosphorus is fixed by aluminum and iron, so that phosphorous availability to plant 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 and oxalate and 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.

Results: Combined application of lime, vermicompost and mineral P significantly increased ($p < 0.05$) labile phosphorus fractions and decreased potential sorption capacities of the soil. As the increased soil pH, reduced exchangeable acidity and oxalate extractable Fe and Al 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 sole application of the amendments.

Conclusions: Combined applications of lime, vermicompost and inorganic P to acidic soils of Goha-1 in Cheha district could convey enhanced amount of available P and ensures the maintenance of higher levels of labile P. It might also contribute towards meeting crop P requirements.

Background

Soil acidity is the most central factor affecting plant growth and limiting crop production (Van Straaten 2007; Fageria 2009; Achieng *et al.* 2010). It is common in regions where rainfall is high enough to leach appreciable amounts of exchangeable bases from soil surface (Achalun *et al.* 2012b). Soil acidification affected large areas of Ethiopian highlands estimated at 40% of the total arable land of the country (Mesfin 2007; Hirpa *et al.* 2013). Particularly, it becomes a serious threat to western and southern highlands of Ethiopia (Wassie and Boke 2009). Soil acidification arises from leaching of bases down the profile through the action of rainfall, continuous cropping, and crop removal of basic cations (Oluwatoyinboet *et al.* 2009). Consequently phosphorus is deficient in most acid soils because soluble inorganic P is fixed by Al and Fe (Adnan *et al.* 2003). This reaction contributes to less availability of P for crops (Chandrasekaran *et al.* 2010).

In highly weathered acidic soils, Fe and Al oxyhydroxides are the dominant species with which P readily interacts (Tan 2000; Sims and Pierzynski 2005; Ahmed *et al.* 2008; 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). These short range crystalline oxyhydroxides (amorphous) are well known to affect P sorption in soils (Janardhanan and Daroub 2010).

In acid soils, high levels of exchangeable Al and Fe play a significant role in controlling orthophosphate concentration in the soil solution (Iyamuremye and Dick 1996; Haynes and Mokolobate 2001; Erich *et al.* 2002). Therefore, crop production on these soils can be improved greatly by adjusting the pH to near neutrality (Whalen *et al.* 2000). The availability of P is influenced by soil organic matter, pH, and exchangeable and soluble Al, Fe, and Ca (Smithson, 1999). Conventionally, large amounts of lime and inorganic P fertilizers are used to saturate Al and Fe ions. This approach alone has not been successful because it is not economical and not environmentally friendly (Ch'ng *et al.* 2014).

Soils contain inorganic P (Pi) and organic P (Po) compounds that are important P sources for plants, but Po rarely represents a major portion of soil P. The inorganic P (Pi) compounds mainly couple with amorphous and crystalline forms of Al, Fe, and Ca (Negassa and Leinweber 2009). 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 (Hedley *et al.* 1982; Reddy *et al.* 1998). These descriptions imply differences among P forms with respect to reactivity in the environment. 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 (Zhang *et al.* 2006; Lan *et al.* 2012).

In natural or agricultural ecosystems having low P soils, mineralization of organic P is the main source of P supply to plants, especially in highly weathered tropical soils (Vincent *et al.* 2010). The contribution of soil organic P to increase available P (labile P) can be more relevant when organic fertilization or other practices which can increase the soil organic matter content (OM) are part of the soil management. Organic fertilization affects the P availability, Pi release (Hue *et al.*, 1994) or microbial immobilization of soil Pi (Chen *et al.* 2000), competition between organic acid anions and phosphate anions for adsorption sites (Andrade *et al.* 2003; Guppy *et al.* 2005). Moreover, Pi compound dissolution by organic acids and metal complexation, particularly of Al³⁺ and Fe²⁺ (Andrade *et al.* 2003), with lower phosphate anion precipitation reactions can occur because of organic fertilization.

The maintenance of adequate amounts of P in the soil and keeping 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 to enhance the fertilizer management strategy (Sharply *et al.* 2004). For example, there is an increasing interest in the potential use of vermicompost (VC) as soil amendment (Lordan *et al.* 2013). Reshid (2016) noted that application of VC showed remarkable improvements in the soil physical and biochemical properties, which in turn enhance the availability of P to plants in acidic soils.

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

P (inorganic and organic fractions) and related properties up on sole or combined applications of organic and inorganic amendments. Studies focusing merely on inorganic P forms have been conducted by Dawit et al. (2002); Wakene and Heluf (2003); Berhane and Sahlemedhin (2003); Shiferaw (2004); Achalu et al. (2014) and 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 (Dawit et al. 2002). Therefore the purpose of this study was to evaluate the effects of sole and combined applications of lime, VC and inorganic P on 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 Cheha district of Gurage zone in south western Ethiopia. The district is situated between 8° 32' 0" and 8° 20' 0" N, and 37° 41' 20" and 38° 2' 40" E, at an elevation that ranges from 900 to 2812 masl. EIAR (2011) classified the area into three agro-ecological zones *i.e.* highlands (2300 - 3200 masl), midlands (1500 - 2300 masl), and lowlands (500 - 1500 masl) 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 are 24.97 and 10.69 °C, respectively. The dominant soil types in the study area are: Nitisols, Leptisols, and Pellic Vertisols [FAO (Food and Agriculture Organization) 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 masl and slope less than 8%. Soil pH was measured at field condition using portable pH meter to select soils having a pH of less than 5.5. The soil samples were put in plastic bag, tagged, and transported to laboratory for analysis. Consequently, about 1 kg of composited soil sample was air dried and ground to pass through a 2 mm sieve for analysis of selected soil properties except organic carbon (0.5 mm sieve) according to the standard methods.

Soil P fractions and other related properties

Different forms of P were determined following the P fractions scheme suggested by Hedley *et al.* (1982) as modified by Chen *et al.* (2000). The oxalate extractable P, Al and Fe (P_{ox} , Al_{ox} and Fe_{ox}) were determined with 0.05 M ammonium oxalate ($(NH_4)_2C_2O_4 \cdot 2H_2O$, pH 3.3) in the dark (McKeague and Day 1966). Citrate bicarbonate dithionite-extractable Fe and Al (Fe_d and Al_d) 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 extractable 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).

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. 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). Phosphorous was determined by the Vanado-molybdate colorimetric procedure using spectrophotometer at 460 nm wavelength. Calcium and Mg were determined by FAAS, as Na, and K were determined with flame photometer. The total N contents of the vermicompost samples were determined by the micro-Kjeldhal method as described by Gavlak *et al.* (2005). Organic matter was determined by the dichromate oxidation method of Walkley and Black (1934). Vermicompost pH values was measured in water (sample: water ratio of 1:5) using a pH meter. The calcium carbonate equivalents (CCE) of the lime was determined by dissolving the lime using excess of standard 0.5 M HCl and followed by gentle boiling. After filtration, the excess HCl was back titrated with standard 0.1 M NaOH solution using phenolphthalein as an indicator. From the amount of NaOH used to neutralize the excess acid of the blank and the filtrate, the CCE values of the lime were calculated.

Incubation experiment

The composited soil sample (0-15cm) was air dried, ground and passed through 2 mm sieve and then 300 g soil was placed in plastic pot in the green house for the next step. Three rates of lime were decided of which two of them 9.20, and 11.50 tons CaCO₃ ha⁻¹ were separately applied to obtain 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 for soil from Goha 1 (SC1) sampling site. The lime used for this particular study had a CCE of 96.15 %. Hence, the actual 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 the 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 of soil and homogenized and the incubation study was conducted for eight weeks as described underneath. 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, 74.51 and 149.01 kg P ha⁻¹ soil) was executed to find out the interaction effects of the treatments in charge. The experiment was laid down in a completely randomized design (CRD) with three replications. Consequently, to the three hundred grams of surface (0-15 cm) air-dried soil (< 2 mm), the specified amount of lime, vermicompost (< 0.25 mm) and solid triple super phosphate (TSP) (sieved <1 mm) were applied jointly or separately. The amended soils were then mixed thoroughly and moistened to field capacity and incubated. Few small holes were made in each container to permit aerobic conditions during incubation. Soil samples were then removed for analysis at 60 days.

Statistical analysis

The study was a factorial experiment in completely randomized design (CRD) with three factors, namely, organic amendments (vermicompost), lime and mineral P. Statistical analysis of the data including Pearson’s simple correlation coefficient, analysis of variance (ANOVA) and comparison of means was executed using Statistical Analysis System (SAS) version 9.1 (SAS Institute, 2004).

Results And Discussion

Physicochemical properties of experimental soil

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 (gcm ⁻¹)	1.32
Field capacity (%)	29.5
Permanent wilting point (%)	19.6
pH (H2O)	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
Alox (mmolkg ⁻¹)	147.37
Feox (mmolkg ⁻¹)	174.69
Phosphorous sorption Capacity (PSC) (mg P Kg ⁻¹)	133.54

Source: Ayenew *et al.* (2018b)

Vermicompost compositions

The vermicompost that has been harvested after sixty days of decomposition was dark brown in color. As depicted in Table 2 the vermicompost prepared by using parthinium, wheat straw, cow dung and poultry manure as a substrate had a pH value of 8.63. Therefore, the pH value obtained for the vermicompost verifies that it could be used for liming the soil. The vermicompost was analyzed for nutrients concentrations and the corresponding values were found N (2.41%), OC (24.40%), and C:N (10.12), P (109.23 ppm), K (577.54 ppm), Ca (1198.28 ppm), Na (127.12 ppm), Mg (137.20 ppm).

Table 2 Characterization of vermicompost

Treatments	pH	OC	N	P	K	Na	Ca	Mg	C:N
		 (%)		 (mg kg ⁻¹)					
VC	8.68	24.40	2.41	109.23	577.54	133.92	1198.28	137.20	10.12

OC = organic carbon, VC = Vermicompost

pH, exchangeable acidity, CEC and available P after Incubation

After eight weeks incubation period the soil was found to have pH ranging from 4.68 to 6.73 (Table 3). It is generally believed that applications of organic materials reduce pH of a soil (Abdala *et al.* 2015). However, contrary to the general contemplation, the results of the present study confirmed that application of vermicompost resulted in higher and significant effect on the pH of studied soils as compared to the control treatment (Table 3). The alkaline reaction in

vermicompost, and the presence of strongly soluble cations in higher concentrations might have contributed to lessening acidic reactions of the soil. In addition, decomposition of vermicompost in soil during incubation might have produced soluble organic acids, which could interact with soil through the oxyhydroxide functional group of clay surfaces and release OH^- to soil solution. Similar results have been reported that vermicompost application alone could have increased the pH of the soil (Gopinath and Mina 2011; Gopinath, *et al.* 2011, Ilker and Tavali 2014).

Analysis of variance also revealed that the application of inorganic P alone had no significant effect on pH of the soil; however the interaction of two factors (lime x inorganic P, lime x vermicompost, inorganic P x vermicompost) and three factors (vermicompost x inorganic P x lime) influenced significantly the pH of the soil (Tables 3). Furthermore, the highest pH (6.73) value of the soil was recorded at combined application of lime, vermicompost and inorganic P (lime x vermicompost x inorganic P) in a proportion amounted 11.50 ton $\text{CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} and 149.01 kg P ha^{-1} whilst, the lowest pH value (4.68) was achieved from the control. The findings of the present study was in concurrent with that of Ashoka *et al.* (2014) which reported addition of inorganic P alone did not have any appreciable effect on soil pH values.

The acidity reduced by lime, vermicompost and inorganic P was synergistic having a mechanism that calcium from lime replaces the exchangeable forms of Al and Fe, which reacts with hydroxide ion released from water in the soil solution forming insoluble Al and Fe hydroxides (Buni, 2015); while compost forms insoluble Al and Fe organic acid complex bounding 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 raise in pH of the studied soil through ligand exchange. In agreement with this, a study revealed that there was a steady increase in the pH of the supernatant solution as sorption progressed, because sorption occurs by the replacement of hydroxyl groups, exposed on surface sites, by phosphate in solution (Goldberg *et al.* 2008).

The results obtained after eight weeks incubation period showed that the amount of available P extracted by Mehlich-III, method ranged from 8.77 to 21.89 mg kg^{-1} at SC1 study site (Table 3). Analysis of variance also revealed that the main factors (vermicompost and inorganic P) applied to soil significantly increased Mehlich-III P content of the soil compared to the control treatment. Similar results have been reported by Ilker and Tavali (2014) showing that vermicompost applied to soil significantly increased available phosphorous. Moreover, statistically significant ($P < 0.05$) influences were observed whenever the three factors are interacted (vermicompost x lime x inorganic P). Consequently, 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 $\text{CaCO}_3 \text{ ha}^{-1}$ and 149.01 kg P ha^{-1} , while the lowest (8.77 mg kg^{-1}) was recorded from the control. The compelling reason for the enhanced increase in available P of soils after incubation could be due to with ability of the lower molecular organic acids (decomposition product of vermicompost) 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 Ca^{2+} , K^+ , Na^+ in vermicompost (organic matter) 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 corresponding decrease in exchangeable acidity from 2.57 $\text{cmol}_c \text{ kg}^{-1}$ in control to 0.31 $\text{cmol}_c \text{ kg}^{-1}$ ($P < 0.05$). The main factors (lime, vermicompost and inorganic P), the interaction between two factors (lime x inorganic P, vermicompost x lime, inorganic P x vermicompost) and three factors (lime x vermicompost x inorganic P) significantly altered the levels of exchangeable acidity in the studied soil (Tables 3). Moreover, the greatest (87.94%) change was obtained from the integrated applications of lime, vermicompost and inorganic P at the rates of (11.50 ton ha^{-1} , 10 ton VC ha^{-1} , 149.01 kg P ha^{-1}), while the lowest (1.53%) was recorded from the control the soil. The reduction in exchangeable acidity can partially be attributed to an initial increase in soil pH that was observed with lime and vermicompost.

Similar analysis showed that except for the sole applications of inorganic P, the other factors including two factors (lime x inorganic P, vermicompost x lime, inorganic P x vermicompost) and three factors interactions (lime x vermicompost x inorganic P) had significant decreasing effects on exchangeable aluminum. It could also be noted that the three factors interaction appeared to have a significant effect and decreased the exchangeable Al of the soil by 88.09 to 95.23% compared to the control, indicating the synergistic effects of the three factors on the exchangeable aluminum in the studied soil. An increase in soil pH might have resulted in precipitation of exchangeable and soluble Al, as insoluble Al hydroxides (Ritchie 1994), thus reducing concentration of Al in soil solution. However, there are other mechanisms involved in the reactions of Al with OM, which 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 adsorption of Al onto the decomposing organic residues (Ritchie, 1994). In agreement with this result, Teshome *et al.* (2017) reported that 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 respectively.

As far as CEC of the soil is concerned, the interactions of three factors had significant ($P < 0.01$) influence on the CEC of the soil (Tables 3). After eight weeks incubation period, CEC values of the soil was found in the range of 22.05 $\text{cmol}_c \text{ kg}^{-1}$ (control) and 29.53 $\text{cmol}_c \text{ kg}^{-1}$ in combined applications of vermicompost, lime and inorganic P at the rates of 10 ton VC ha^{-1} , 11.50 ton $\text{CaCO}_3 \text{ ha}^{-1}$, and 149.01 kg P ha^{-1} . Sole applications of inorganic P had no significant effect on CEC of incubated soil (Table 3). The possible reason for the enhancement of CEC during combined (lime x vermicompost x inorganic P) application of those amendments could be the increase in pH of the soils. Because with increasing pH (i.e. increasing activity of OH^- ions) H^+ is dissociated from oxide surfaces or from organic functional groups, thus resulting in a negative charge, which could be allied with the CEC of the soils.

Table 3 Effects of amendments on selected chemical properties of soil (SC1)									
				exAc	exAl	CEC	Mehlich 3 P	PAcs	PAIs
Treatments		pH	(cmol _c kg ⁻¹)		 (mg/kg)...		 (%)		
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
		L3	6.71ba	0.35n	0.03j	29.45a	13.17l	1.59n	0.12j
P1	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; PAc = percentage of acid saturation; PAl = 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 incubation of the soil is presented in Tables 4. In view of a study results reported by Asmare *et al.* (2015) on eight Ethiopian acidic soils the soil considered in the current study had high oxalate extractable Al and Fe and dithionite citrate bicarbonate extractable Al and Fe (Ayenew *et al.* 2018a). Since oxalate and dithionite extractable iron and aluminum contents of the soil were high; Fe and Al oxyhydroxides could be the dominant species with which P interacts. 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.

Data showing main and interaction effects of treatments on oxalate extractable aluminium (Al_{ox}) are exhibited in Table 4. The highest (152.64 mmol kg^{-1}) value of Al_{ox} from sole application of vermicompost at the rate of 10 ton ha^{-1} and the least (141.93 mmol kg^{-1}) from the integrated applications of lime, vermicompost and inorganic P were recorded for the soil. Thus, the highest (6.85%) reduction in oxalate extractable Al was obtained from combined applications of lime, vermicompost and inorganic P at the rates of 9.20 $\text{ton CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} and 149.01 kg P ha^{-1} . After a given incubation period the results of analysis of variance revealed that sole (inorganic P, lime and vermicompost), combined applications of the amendments had significant ($p < 0.01$) effect on the oxalate extractable aluminum over the control (Table 4).

The effects of treatments on dithionite citrate bicarbonate extractable aluminium (Al_d) are also presented in Table 4. In the interim sole and integrated applications of amendments had substantial ($p < 0.01$) influence on dithionite citrate bicarbonate extractable aluminum (Al_d). Consequently, the highest (173.77 mmol kg^{-1} dithionite citrate bicarbonate extractable (Al_d) 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 $\text{ton CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} and 149.01 kg P ha^{-1} .

The effects of treatments on oxalate extractable iron (Fe_{ox}) are also shown in Table 4. The values of Fe_{ox} obtained after incubation was ranged from 88.59 - 96.39 mmol kg^{-1} in which the maximum (96.39 mmol kg^{-1}) was recorded from the application of vermicompost at the rate of 10 ton ha^{-1} alone and the least (88.59 mmol kg^{-1}) recorded from the integrated applications of lime vermicompost and inorganic P at the highest rates. The highest value obtained from sole application of vermicompost may be ascribed to organo-metal complex formed during the incubation period. It has been reported that 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 noncrystalline Al and Fe increases (Kang *et al.* 2009). A significant ($p < 0.01$) decreases in oxalate (Fe_{ox}) and dithionite extractable iron (Fe_d) were observed as a result of integrated applications of lime, vermicompost and inorganic P as two factors (lime x inorganic P, lime x vermicompost, inorganic P x vermicompost) and three factors (vermicompost x lime x vermicompost x inorganic P) compared to the control. Accordingly, the maximum (9.32%) reduction in Fe_{ox} at the exchange sites was recorded from integrated applications of lime, vermicompost and inorganic P at the rates of 11.50 $\text{ton CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} and 149.01 kg P ha^{-1} respectively, whereas the least (1.34%) was obtained from the sole application of vermicompost at the rates of 10 ton ha^{-1} .

Similarly, amalgamated applications of these amendments at the rates of 11.50 $\text{ton CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} and 149.01 kg P ha^{-1} had brought the maximum (1.73%) reduction in Fe_d , and the least (0.16%) variation from the control compared to the native soil. Similar results were reported by Asmare *et al.* (2015) who found that individual and combined applications of organic and inorganic minerals had significant effect on oxalate (Al_{ox} , Fe_{ox}) and dithionite (Al_d , Fe_d) extractable aluminum and iron free oxides.

It could be noted that synergistic effects of the three factors on the oxalate and dithionite extractable Fe and Al were remarkable. 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 $\text{Al}(\text{OH})_3$ as a result of applications of liming materials. 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, adsorption reaction through which soil interacts with foreign materials; i.e along with the application of inorganic P the amount of phosphate adsorbed on metal oxyhydroxides increased and this could reduce free metallic oxides at exchange sites. In this regard, the results of the present study were in concomitant with that of Asmare *et al.* (2015), in which the reductions in Al_{ox} , Fe_{ox} , Al_d and Fe_d contents as the result of application of P bearing materials to a soil was reported and justified by the fixation of Al and Fe in the form of Al-P and Fe-P as a cause for reduction in amount extracted by oxalic acid.

Ammonium oxalate extractable phosphorous is associated with oxalate extractable iron and aluminum, because Fe and Al oxyhydroxides are good indicators for P sorption as they act as a sink for soluble phosphates (Vaananen *et al.* 2008). It is a potentially useful measure of the P associated with the amorphous iron and aluminum oxides in the soil (Wolf and Baker 2008). In the current study, upon the exclusive (main factor), integrated [two factors (lime x vermicompost, inorganic P x lime, vermicompost x inorganic P) and three factors (lime x vermicompost x inorganic P)] applications to soils for eight weeks incubation period appreciable ($p < 0.001$) differences in oxalate extractable P (P_{ox}) were observed in the soil. In the case where integrated application of amendments (lime x vermicompost x inorganic P) at the rates of 11.50 $\text{ton CaCO}_3 \text{ ha}^{-1}$, 10 ton VC ha^{-1} and 149.01 kg P ha^{-1} was executed, the highest (8.70

mmol kg⁻¹) was achieved whereas the lowest (5.88 mmol kg⁻¹) recorded from the control. It can be observed that as the amount of oxalate and dithionite extractable form of those metal oxides reduced from the exchange sites, phosphorous extracted by ammonium oxalate (P_{ox}) obviously 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 mainly attributed to P adsorbed on amorphous metal oxides (Fe_{ox} and Al_{ox}) (Cui *et al.* 2017).

Phosphorous sorption capacities was significantly (P<0.05) influenced by the main and joined applications of treatments (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 due to combined applications of the treatments (lime x vermicompost x inorganic P) at the rates of 9.20 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹, and 149.01 kg P ha⁻¹. It can also be seen that the adsorption capacity of the soil decreased significantly with increasing applications rates of integrated amendments while applications of vermicompost solely increased the sorption capacity of the two soils under study. The increased adsorption capacity of the soil because of the exclusive application of vermicompost may be due to hindrance of crystallization of Fe and Al oxides. 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 increases (Borggaard *et al.* 1990; Kang *et al.* 2009). The reduction in magnitude of phosphorous sorption capacities due to integrated application could be attributed to the coating of metal oxyhydroxides 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 reduces adsorptions of phosphate on the exchange site and addition of inorganic P, which occupy the exchange sites where P is expected to be adsorbed. Thus, the result of the present study is in concurrent with the study made by Gikonyo *et al.* (2011), which showed that sole or integrated applications of P sources (organic and inorganic) had a significant effect on the PSC of a soil.

The change in DPS of the soil was presented in Table 4. The phosphate ion is negatively charged and hence, 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 (Barrow *et al.* 1998; 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). Furthermore, recent studies have shown that the degree of P saturation (DPS) is a good indicator of the soil's potential to release P (Hooda *et al.*, 2000).

The incubated soil was found to have DPS (%) values ranging from 4.49-7.06%. The DPS (%) value was significantly (P<0.01) affected by individual (lime, vermicompost, inorganic P) and combined applications of these treatments (Table 4). The maximum DPS (7.06%) value was recorded from the integrated applications of (lime x vermicompost x inorganic P) amendments at the rates of 11.50 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹, and 298.03 kg P ha⁻¹. Whereas the minimum DPS (4.49%) value was observed from the control, Thus, the result of present study is in concurrent with the study made by Gikonyo *et al.* (2011) which showed that sole or integrated applications of P sources (organic and inorganic) had a significant effect on the DPS of soils. It can be inferred that the observed increase in the DPS of the soils as a result of application of these amendments might have brought the better mobility of P in the soils. In this regard Yan *et al.* (2017) reported that due to decrease of the sorption sites for further P sorption, the concentrations of exchangeable P increased with increasing DPS and soil P mobility increases.

Table 4 Effects of amendments on Oxalate and dithionite extractable iron, Aluminum and phosphorous of SC1 Soil									
		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	4.499n
		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
	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
		L3	142.99l-o	169.95c-g	89.79h-l	624.61klm	8.61bac	124.31lm	6.93ab
P2	V0	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
		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
	V1	L0	145.97b-g	170.73b-f	91.11b-i	625.91g-k	8.28d	126.60c-g	6.54c
		Continues...							
		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
	V2	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; 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 forms and distributions of P

The combined and sole applications of the amendments altered significantly the chemical properties expected to impact the distributions of phosphorous in the soil (Table 5). The forms and distribution of the various P fractions [NH₄Cl-P, NaHCO₃-Pi, NaHCO₃-Po NaOH-Pi, NaOH-Po (NaOH-Pi)_{sn}, (NaOH-Po)_{sn} HCl-Pi, residual P and total P] following incubation of the soil are shown in Table 5 too. After eight weeks incubation period, the distributions and forms of Pi were in the order of magnitude: NH₄Cl-P < NaHCO₃ - Pi < (NaOH-Pi)_{sn} < HCl-Pi < NaOH-Pi. The highest percentage change in each fraction was recorded from the interactions of three factors (lim x vermicompost x inorganic P) whereas; the lowest was obtained from the control. Results of the analysis of variance also indicated that integrated applications of both two factors (lime x vermicompost x inorganic P) and three factors (lim x vermicompost x inorganic P) amendments had statistically significant ($P < 0.01$) effect on the amount and distributions of NH₄Cl-P, NaHCO₃-Pi, NaOH-Pi)_{sn}, HCl-Pi, and NaOH-Pi fractions in the soil.

The distributions of easily mineralisable (NaHCO₃)-Po and less labile (NaOH)-Po were in the order of magnitude: NaOH-Po < (NaOH-Po)_{sn} < NaHCO₃-Po. The highest percentage change in each fraction was recorded from the interactions of three factors (lime x vermicompost x inorganic P) and the lowest was obtained from the control. According to analysis of variance all the treatments influenced significantly ($p < 0.01$) the amount and distributions of the extracted organic form of P (Tables 5).

The NaOH-Pi was the largest extractable inorganic P fraction and the most abundant active P form 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 (and to a lesser extent NaOH-Po) (Iyamuremye *et al.* 1996; Li *et al.* 2015). The increase of this fraction observed in these soils amended by phosphorus fertilizer and vermicompost was possibly as a result of phosphate released from phosphorus fertilizer and vermicompost. Similar result has been reported by Pavan and Andmcioli (1995) where application of compost was able to promote NaOH-Pi. It can be deduced that since NaOH-Pi fraction is a site for P sorption; increase in this fraction provide evidence that P-rich amendments in the studied soil may decrease future P sorption in soil by reacting with these sorption sites (Daly *et al.* 2001; Yan *et al.* 2013). This result is also in concomitant with what has been reported by Elias *et al.* (2010) that goat manure and inorganic phosphate addition influenced NaOH-P_i to greater extent.

After eight weeks of incubation period the least (2.04 mg kg⁻¹) concentration of the readily available NH₄Cl extractable P (Gunatilaka, 1988), was recorded from the control and the highest (33.37 mg kg⁻¹) was obtained from the combined applications of lime, vermicompost and inorganic P at the rates of 11.50 ton CaCO₃ ha⁻¹, 10 ton VC ha⁻¹, 149.01 kg P ha⁻¹ respectively.

According to the result of the present study (Table 5) lime alone had no significant effect on readily available fractions (NH₄Cl-P) at both study sites. Contrasting result was mentioned by Hartono *et al.* (2000) that lime had significant effect on readily available Pi but it agrees with that of Iyamuremye *et al.* (1996) where lime didn't affect readily available Pi. Even though sole applications of lime didn't appreciably affect the readily available fractions of P (NH₄Cl-P) the magnitude of enhancement varied along with the rates of lime. This change in magnitude may be attributed to the decrease of exchangeable Al that is precipitated by OH⁻. In the case where lime was applied in combination with other materials like inorganic P and vermicompost, significant differences were observed over the control (Table 5). On the other hand, the readily available fraction (NH₄Cl-P) was significantly affected by single or combined applications of inorganic P and vermicompost as compared to the control.

The HCl-Pi fraction is associated with the primary minerals such as apatite (Tiessen *et al.* 1984) and with calcium-bound P, which is little or missing in highly weathered soils (Walker and Syers 1976). In the present exploration, it appeared that integrated applications of the amendments of two factors (lime x vermicompost, inorganic P x lime, vermicompost x inorganic P) and three factors (lime x vermicompost x inorganic P) tended to enhance HCl-Pi significantly (Table 5). Consequently, the highest value of HCl-Pi was recorded from the interaction of lime, vermicompost and inorganic P, at the respective maximum rates, whereas the lowest was recorded from the control. However, in the current study, HCl-P did not varied significantly with the sole applications of those treatments. The absence of substantial changes in HCl-Pi is explicable because the soil is acidic which would favor formation of Al and Fe P inorganic compounds over Ca products (Hartono *et al.* 2000). Similar result was reported by Pavan and Androcioili (1995) that application of compost didn't significantly influence HCl-Pi. Hartono *et al.* (2000) found that applications of inorganic phosphorous or lime to acidic soils had no significant effects on the concentrations of HCl-Pi.

Generally, the dynamics of the two labile P fractions (NH₄Cl-P, NaHCO₃-P_i) varied considerably ($p < 0.05$) when combined applications of lime, vermicompost and inorganic P were executed at both sampling sites. Whilst, 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 (NaHCO₃)-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			NH4Cl-pi	NaHCO3-pi	NaHCO3-po	NaOH-pi	NaOH-po	NaOH-pi)sn	NaOH-po)sn	HCl-pi	
(Kg ha ⁻¹)											
			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	
	Continues...										
		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
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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; PAc = percentage of acid saturation; PAl = 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.

Correlation among soil properties

The correlation between soil properties after incubation with amendments is exhibited in Table 6. 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 P_{ox}. This could be an indication for the presence of higher concentration of NH₄Cl extractable P in soils where there are prominently higher concentrations of Mehlich 3-P, NaHCO₃-Pi, NaHCO₃-Po, HCl-P, NaOH-Pi, NaOH-Po and P_{ox} in the soil. In addition, the correlation result verified the scientific speculation that P_{ox} thought to be P adsorbed initially (native P) and 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. Therefore, up on additions of P bearing amendments to soils having higher P_{ox} only smaller amounts of P tend to be adsorbed and the remaining P would be forced to soil solution and become available. According to the correlation result from incubated soils, enhanced amount of available P was manifested where there was higher HCl extractable P (Ca bound P) as liming materials are applied. The strong rationale for strong positive association between HCl-P and readily available P might be the occurrence of dissolution rather than precipitation in acidic soils.

Meanwhile, those readily available fractions of P (NH₄Cl-P, NaHCO₃-Pi and NaHCO₃-Po) in the studied soils had strong and negative association 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. This could be an indication for reduction in free metallic oxyhydroxides (Al_{ox}, Fe_{ox}) and PSC with increasing amount of P added through inorganic P and vermicompost application as well as lime.

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**	0.26**	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**

Conclusions

It can be seen that unlike separate applications of inorganic P, both lime and vermicompost had significant effect in enhancing the pH of the studied soil. Combined application of lime, vermicompost and inorganic P is more effective in reducing exchangeable acidity, exchangeable aluminum compared to the single treatment. Even though, sole applications of lime, vermicompost and inorganic P had significant effects on Mehlich-III extractable available P; combined applications of these amendments had brought higher and better available P. Oxalate and dithionite citrate bicarbonate extractable Fe and Al, which indicate the potential adsorption capacity of soils, could be reduced significantly by combined use of the treatments over single applications. Despite having no significant effects on the distributions of P forms, sole application of lime with increasing rates reduced the magnitude of NaOH extractable P and enhanced the readily available P fractions (NH₄Cl-P, NaHCO₃-Pi and NaHCO₃-Po).

Therefore, combined applications of lime, vermicompost and inorganic P to acidic soils of Goha-1 in Cheha district could convey enhanced amount of available P. It can also ensure the maintenance of higher levels of labile P in the soil and highly significantly influenced those soil properties as well. Sole

application of inorganic P and vermicompost increased the labile inorganic P fractions in the soil and decreased the potential sorption capacities of the soil. It can be concluded that integrated applications of these amendments could contribute towards meeting crop P requirements. Therefore, the smallholder farmers and stakeholders in the study area should implement technologies like low input P management strategy and application of lime, to alleviate phosphorous and acidity related problems.

Abbreviations

ANOVA
Analysis of variance
CCE
Calcium carbonate equivalents
CEC
Cation exchange capacity
CRD
Completely randomized design
DPS
Degree of P saturation
EIAR
Ethiopian institute of agricultural research
FAAS
Flame atomic absorption spectroscopy
FAO
Food and Agriculture Organization
PSC
Phosphorous adsorption capacity
OM
Organic matter
SAS
Statistical Analysis System
TSP
Triple super phosphate
VC
Vermicompost

Declarations

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Competing interest

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Authors' contributions

Bereket Ayenew collected, analyzed, interpreted the data and made the final write up. Asmare Melese as a co-authors edited and approved the final manuscript

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