

Full Length Research Paper

Impact of Organic and Inorganic Amendments on Acidic Soil Chemistry

Asmare Melese^{1*} and Markku Yli-Halla²

¹Department of Plant Science, Debre Berhan University, Ethiopia.

²Department of Food and Environmental Sciences, University of Helsinki, Finland.

Received 18 February, 2024; Accepted 9 October, 2024

An incubation study was conducted for two months to evaluate the effects of different treatments on the inorganic P fractions and other chemical properties on an acidic soil. Four rates of lime and wood ash (3.5, 7.0, 9.2, 11.2 tons CaCO₃ equivalent ha⁻¹) were separately applied to obtain target soil pH values of 5.5, 6.0, 6.5 and a lower pH obtained with half of the lime requirement needed to bring the pH to 5.5. Three rates of mineral P fertilizer and manure P (32.5, 65, 130 kg P ha⁻¹) were separately applied into the whole soil volume. Additionally, wood ash (7 tons CaCO₃ ha⁻¹) and lime (7 tons CaCO₃ ha⁻¹) were combined separately with each of the manure and mineral P rates. The experiment was laid down in a completely randomized design with two replications. Lime and wood ash treatments showed a significant effect on the pH and exchangeable acidity compared to manure. The highest lime and wood ash rates (11.2 tons CaCO₃ ha⁻¹) increased the pH from 4.89 to 6.03 and 5.93; decreased the exchangeable acidity from 2.22 to 0.14 and 0.16 cmol_c kg⁻¹, respectively. The maximum increment in Olsen P by 132%, aluminum bound P (Al-P) by 160%, iron bound P (Fe-P) by 22% and oxalate extractable P (P_{ox}) by 33% were observed by the application of mineral P at 130 kg P ha⁻¹ plus wood ash (7.0 tons CaCO₃ ha⁻¹). Therefore, lime and wood ash applications in acidic soils can effectively ameliorate H⁺ and Al³⁺ toxicity and P deficiency.

Key words: Acidity, incubation, lime requirement, P form.

INTRODUCTION

Acid soils limit crop production on 30 to 40% of the world's cultivated land and up to 70% of the world's potentially arable land (Haug, 1983). Different reports

have also indicated that there is significant soil acidity coverage in Ethiopia (Wassie and Shiferaw, 2009). Hence, it is a serious threat to crop production in most

*Corresponding author. E-mail: asmaremelese@gmail.com. Tel: +251912630687.

Author(s) agree that this article remain permanently open access under the terms of the [Creative Commons Attribution License 4.0 International License](https://creativecommons.org/licenses/by/4.0/)

highlands of Ethiopia and a major crop production constraint in the small scale farmers of the country.

The two fundamental factors limiting the fertility of acid soils are nutrient deficiencies such as P, Mo, Ca, Mg and K and the presence of phytotoxic substances such as soluble Al and Mn. The low P status of highly weathered acid soils is a particular problem because large amounts of P need to be applied in order to raise concentration of available soil P to an adequate level (Sanchez and Uehara, 1980). Low P status is partially attributable to continuously negative P balances and partially to inherent soil properties. These soils contain large quantities of Al and Fe hydrous oxides which have the ability to adsorb P onto their surfaces. Thus, much of the added P is fixed and is not readily available for crop use (Srivastava et al., 1969; Sharma et al., 1980; Tomar et al., 1984). Tekalign and Haque (1987), Lupwayi and Haque (1996) and Shiferaw (2004) indicated that most of the highland soils of Ethiopia are P deficient.

Soil P occurs as inorganic and organic forms and their relative distribution varies with climate, vegetation, parent materials and soil management practices (Fairhurst et al., 1999). Inorganic P forms are divided into two groups such as active forms which include Al-P, Fe-P and calcium bound P (Ca-P) and inactive forms which include occluded aluminium-iron bound P (occl-Al-Fe-P) and reductant soluble Fe bound P (red-Fe-P) (Walker and Syers, 1976). The active inorganic P fractions are the most available forms to plants, with the degree of availability increasing in the order of Ca-P, Fe-P and Al-P under well drained conditions (Walker and Syers, 1976). Soil drainage condition is one of the factors that affect available soil P. For example, P availability will be higher in flooded soil because the flooding results in reducing conditions which change the previously insoluble ferric phosphate to more soluble ferrous phosphate (Fageria, 2009).

There are considerable evidence in literature suggesting that application of lime, wood ash, manure and mineral P fertilizers can be used for the control of acidity related problems and P deficiency in acid soils. Liming and application of phosphate fertilizers as organic or inorganic P forms have been suggested for the control of P deficiency problems in acid soils (Opara-Nadi, 1988).

In acid soils with high levels of exchangeable Al, organic matter (OM) plays a significant role in the reduction of P adsorption and increased P availability due to cumulative effects of several mechanisms (Erich et al., 2002; Opala et al., 2010). These include release of inorganic P from decaying residues, blockage of P adsorption sites by organic molecules released from the residues, a rise in soil pH and complexation of soluble Al and Fe by organic molecules (Iyamuremye and Dick, 1996).

Lime and wood ash applications increased pH of acidic soils and resulted in a decrease in P adsorption. This

may be due to the increased concentration of hydroxyl ion (OH⁻) that increase surface negative charge and leading to competition with P ions for adsorption sites and increased P availability (Fageria, 2007; Mweta et al., 2007; Kisinyo et al., 2013). In addition to its liming effect, wood ash contains P and can be used to alleviate P deficiencies better than lime (Adetunji, 1997; Nkana et al., 2002; Saarsalmi et al., 2006; Awodun et al., 2007; Insam et al., 2009).

Although much of the Ethiopian highlands have a high potential for crop production, almost no detailed work has been done on effect of different amendments on the status, forms and dynamics of P in the soils. Therefore, the objective of this study was to evaluate the effects of applications of lime, wood ash, manure and mineral P fertilizers on available P, inorganic P forms, oxalate extractable P (P_{ox}), degree of P saturation and other selected soil chemical properties on acid soil of Farta District, Northwestern Highlands of Ethiopia.

MATERIALS AND METHODS

Description of the study area

The study was conducted in Gassay area of Farta District in South Gondar Zone of the ANRS (Figure 1). The District lies between 11° 32' and 12° 03' N latitude and 37° 31' and 38° 43' E longitude, and covers an estimated area of 1118 km² within the altitude range of 1900 to 4035 m above sea level (masl). In terms of topography, 45% of the total area is gentle slope, while flat and steep slope lands account for 29 and 26%, respectively.

According to the Regional Office of Planning for Northwestern Ethiopia (1985), geologically the study area is covered with thick trap series volcanic rocks which were erupted from fissures during the early and middle Tertiary and from Choke Shield volcanic mountain center during the Miocene and Pliocene. The trap volcanic series consists mainly of weathered and jointed basalt. The soils of the study area are developed from the parent materials of volcanic origin, predominantly Tertiary basalt. The majority of the soils in Farta District are Luvisols (FAO, 1981). The soils of the study area have not been classified according to U.S. Soil Taxonomy, but tentatively many of them are likely to fall in the Alfisols order. Luvisols are potentially suitable for a wide range of agricultural uses because of their favorable physical characteristics and moderate chemical fertility.

Considering land use, an estimated 64.7% of the area is cultivated for different annual and perennial crops, while areas under grazing and/or browsing, forests and shrubs, settlements, and wastelands account for about 10.2, 0.6, 7.8 and 16.7%, respectively. The natural vegetation in the study area consists of some tree species that are remnants of a once dense evergreen forest occurring on slopes and sparse grass complex in various areas. The dominant tree species in the area include *Juniperus procera*, *Olea africana* and *Hajenia abyssinica*. Currently, refilling or replantation strategy is being implemented in the study area (WOARD, 2005). The rural households are engaged primarily in crop-livestock mixed farming systems. Barley, wheat, teff, sorghum, maize, faba beans, peas and potatoes are dominant crops while chickpeas and some oil crops are also grown.

The average minimum, maximum and mean temperatures are 9.3, 22.3 and 15.8°C, respectively (Figure 2). The rainfall pattern is unimodal, stretching from May to September. The mean annual

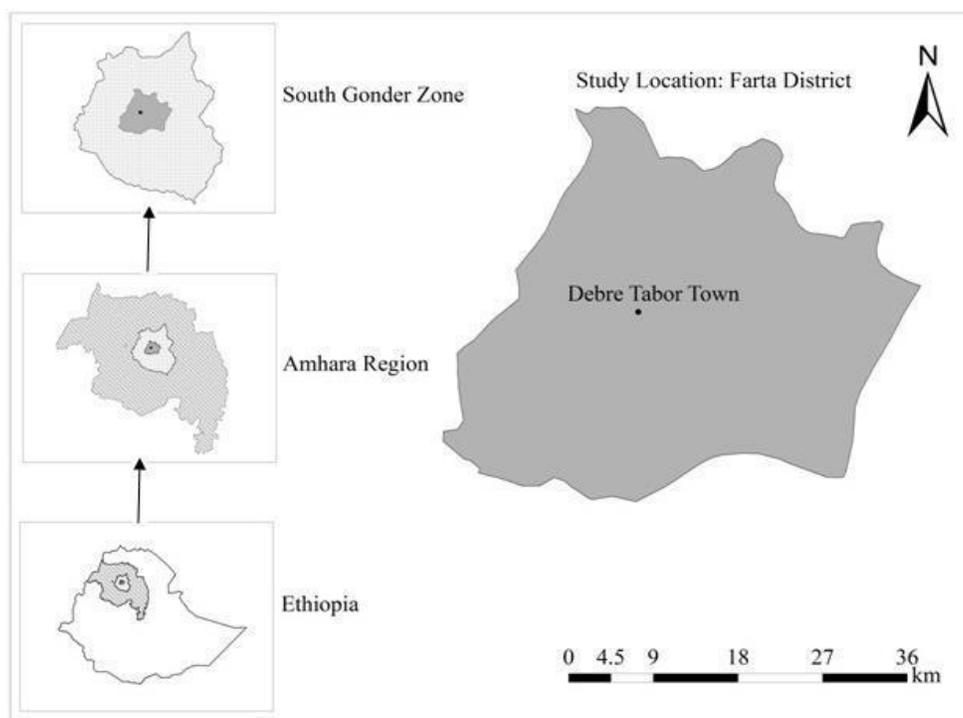


Figure 1. Location map of the study area.

rainfall is 1445 mm (NWRMSA, 2010).

Soil sample collection and analysis

A bulk soil sample was taken from the top soil (0 to 20 cm) from the very strong acidic soil of Gassay area in Farta District, Northwestern Highlands of Ethiopia. The soil was air dried, ground and passed through a 2 mm sieve and analyzed for selected chemical and physical properties according to standard laboratory procedures.

Analysis of soil physicochemical properties

Soil particle size distribution was analyzed by the Bouyoucos hydrometer method as described by Day (1965). Soil bulk density was measured from three undisturbed soil samples collected using a core sampler (2.5 cm radius and 5.0 cm height) as per the procedures described by Jamison et al. (1950).

Soil pH (1:2.5) was measured potentiometrically in water solutions using a combined glass electrode pH meter (Chopra and Kanwar, 1976). The potential CEC of the soil was determined from soil samples saturated with NH_4^+ at pH 7.0, subsequently replaced by K^+ from a percolated 1 M KCl solution. The excess salt was removed by washing with ethanol and the NH_4^+ that was displaced by K^+ was measured using the micro-Kjeldahl procedure (Chapman, 1965) and reported as CEC. Total exchangeable acidity was determined by saturating the soil samples with 1 M KCl solution and titrated with 0.02 M NaOH as described by Rowell (1994). From the same extract, exchangeable Al in the soil samples was determined by application of 1 M NaF which form a complex with Al and released NaOH and then NaOH was back titrated with a standard solution of 0.02 M HCl.

Total carbon, all assumed to be OC, and total N contents of the soil sample was determined using the Vario MAX elemental analyzer by the dry oxidation method. Available P was determined both by Olsen and Bray I methods. The analysis of P by Olsen method was carried out by shaking the soil samples with 0.5 M NaHCO_3 at nearly constant pH of 8.5 in 1:20 of soil to solution ratio for half an hour as described by Olsen et al. (1954). The Bray I P analysis was carried out by shaking the soil samples with an extracting solution of 0.03 M NH_4F in 0.1 M HCl for 1 min as described by Bray and Kurtz (1945). The inorganic P fractions were successively extracted with 1 M NH_4Cl , 0.5 M NH_4F , 0.1 M NaOH, 0.25 M H_2SO_4 , 0.3 M Na-dithionite and Na-citrate bicarbonate solution, and 0.1 M NaOH to estimate easily soluble P, Al-P, Fe-P, Ca-P, reds-Fe-P and occl-Al-Fe-P, respectively, according to the procedure by Chang and Jackson (1957). The oxalate extractable P, Al and Fe (P_{ox} , Al_{ox} and Fe_{ox}) were extracted with 0.05 M ammonium oxalate ($(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$, pH 3.3) for two hours in the dark (Niskanen, 1989). The suspension was centrifuged and filtered through a Whatman No. 42 filter paper to get a clear solution. The extracts were analyzed for P, Al and Fe by inductively coupled plasma optical emission spectroscopy (ICP-OES). Dithionite citrate bicarbonate-extractable Fe and Al (Fe_d and Al_d) were determined by the method of Mehra and Jackson (1960). The extracts were analyzed for Al and Fe by ICP-OES.

The P sorption capacity (PSC, mmol kg^{-1}) of the soil was calculated as the sum of the concentrations of oxalate-extractable metals (Fe_{ox} and Al_{ox} , mmol kg^{-1}) according to Hartikainen et al. (2010) as:

$$\text{PSC} = \text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}$$

The degree of P saturation (DPS, expressed as %) was determined as the percentage of the ratio of the oxalate extractable P (P_{ox} , mmol kg^{-1}) to the sorption capacity as follows:

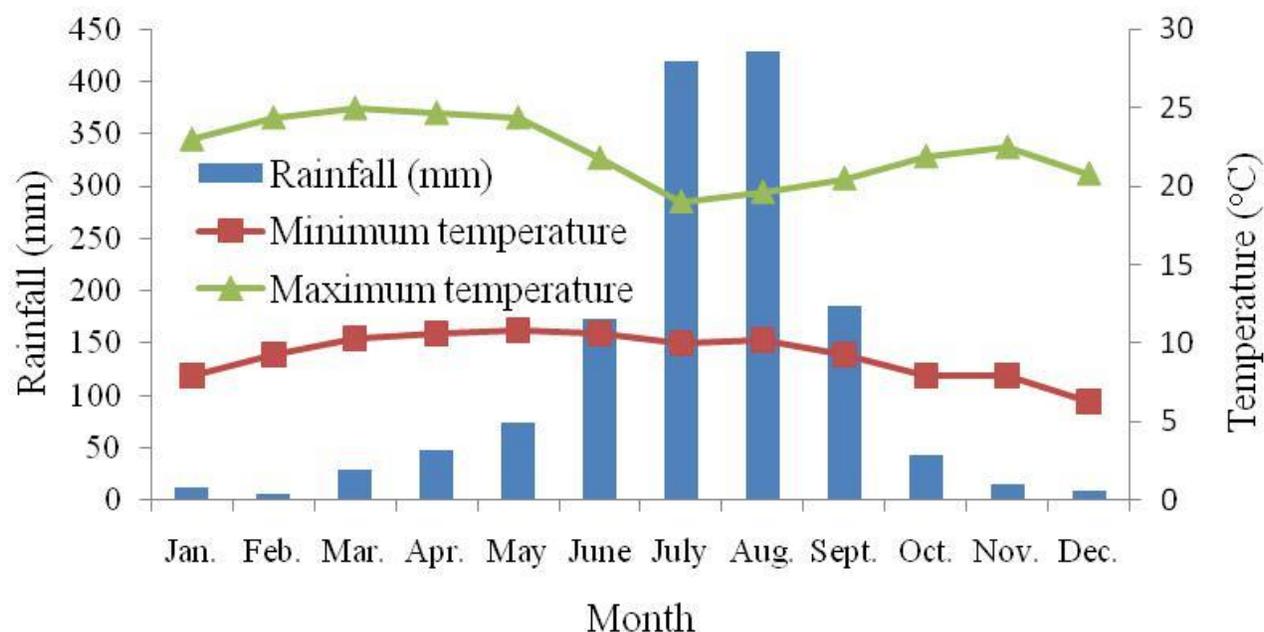


Figure 2. Mean monthly rainfall and mean monthly maximum and minimum temperatures of the study area.

$$\text{DPS} = (P_{\text{ox}}/P_{\text{SC}}) \times 100\%$$

DPS was also calculated separately for Al_{ox} and Fe_{ox} as:

$$\text{DPS } \text{Al}_{\text{ox}}\text{-P} = (\text{Al-P}/\text{Al}_{\text{ox}}) \times 100\%$$

$$\text{DPS } \text{Fe}_{\text{ox}}\text{-P} = (\text{Fe-P}/\text{Fe}_{\text{ox}}) \times 100\%$$

Analysis of the composition of manure, wood ash and lime

Total contents of P, Ca, Mg, K, Na, Al and zinc (Zn) in the cow dung manure and wood ash from the wood of *Eucalyptus* tree were measured in suspensions obtained after ashing at 500°C, dissolution with 0.2 M HCl and digestion on a hot plate. Phosphorus was determined by the vanado-molybdate colorimetric procedure using spectrophotometer at 460 nm wavelength based on standard laboratory procedure. Calcium, Mg, K, Na, Al and Zn were determined with ICP-OES. The total N contents of the manure and the wood ash samples were determined by the micro-Kjeldhal method as described by Jackson (1967).

The pH and EC of the manure and wood ash were measured in water (sample: water ratio of 1:5) using a pH meter and conductivity meter, respectively. The calcium carbonate equivalents (CCE) of the wood ash and the Dejen lime were determined by dissolving the wood ash and 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 both the wood ash and the lime were calculated.

Incubation study

The incubation study was conducted for two months as described below. The composite soil sample was air dried ground and passed with 2 mm sieve and then 0.5 kg soil was placed in plastic pot and

mixed with different treatments in a greenhouse. Four rates of lime and wood ash (3.5, 7.0, 9.2 and 11.2 tons CaCO_3 equivalent ha^{-1}) were separately applied to obtain target pH values of 5.5, 6.0, 6.5 and a lower pH obtained with half of the lime requirement needed to bring the pH to 5.5. The lime and the wood ash used for this particular study had a CCE of 94.6 and 71.7%, respectively. Hence, the actual field application rates of lime were 0, 3.69, 7.37, 9.69 and 12.22 tons lime ha^{-1} ; the wood ash rates were 0, 4.88, 9.67, 12.83 and 16.18 tons wood ash ha^{-1} . The rates of wood ash expressed based on its P content were 61, 121, 159 and 194 kg P ha^{-1} (23, 46, 61 and 74 mg P kg^{-1} soil).

Three rates of manure P (12.5, 25.0 and 50.0 mg P kg^{-1}) or (32.5, 65.0 and 130 kg P ha^{-1}), based on its total P content, were applied uniformly to the whole soil volume. The actual field application rates of manure were 3.414, 6.828 and 13.655 tons manure ha^{-1} . Three rates of mineral P fertilizer (12.5, 25 and 50 mg P kg^{-1} soil) or (32.5, 65.0 and 130 kg P ha^{-1}), as triple superphosphate (TSP), were separately applied uniformly to the whole soil volume. The manure was ground and passed through a 0.25 mm sieve. Wood ash (7 tons CaCO_3 ha^{-1}) and lime (7 tons CaCO_3 ha^{-1}) were combined separately with each of the manure P and mineral P fertilizer rates as additional treatments. A control treatment with no soil amendments was used for the incubation experiment. A total of 54 pots were used for the incubation experiment. The experiment was laid down in a completely randomized design with two replications. The units of the treatments were converted into hectare bases by assuming that the plough depth is 20 cm and the bulk density of the soil is 1.3 g cm^{-3} . All pots were subjected to wetting and drying cycles during the incubation period.

Statistical analysis

Analysis of variance was carried out on the effect of treatments on the inorganic P fractions and selected chemical properties of the soil using the generalized linear model (GLM) procedure of the Statistical Analysis System (SAS) software version 9.00 (SAS Institute, 2004). Duncan's Multiple Range Test was employed to

Table 1. Selected physical and chemical properties of the experimental soil.

Parameter	Value
Sand (%)	26
Silt (%)	31
Clay (%)	43
Bulk density (g cm ⁻³)	1.3
pH (H ₂ O)	4.88
Cation exchange capacity (cmol _c kg ⁻¹)	24.7
Exchangeable acidity (cmol _c kg ⁻¹)	2.31
Exchangeable Al (cmol _c kg ⁻¹)	1.50
Organic carbon (%)	1.96
Total nitrogen (%)	0.17
Bray I P (mg kg ⁻¹)	5.7
Olsen P (mg kg ⁻¹)	7.0

Table 2. Chemical characterization of manure and wood ash.

Amendment	pH-H ₂ O (1:5)	EC (dS m ⁻¹)	CCE	N	P	Ca	K	Mg	Na	Al	Zn
										mg kg ⁻¹	
Manure	8.0	6.01	-	1.69	0.475	1.20	1.45	0.63	0.19	16675	105
Wood ash	12.3	9.33	72	0.05	1.240	15.9	2.23	2.64	0.22	155	3

EC = electrical conductivity; CCE = calcium carbonate equivalent.

test the significance difference between means of treatments.

RESULTS AND DISCUSSION

Initial soil properties, manure and wood ash compositions

The soil used for the incubation experiment was clayey in texture (Table 1). The value of the Olsen extractable P was 7.0 mg kg⁻¹ which was in the low range of P content (Cottenie, 1980) and the pH was 4.88 which was in the very strongly acidic soil reaction range (Jones, 2003) (Table 1). The soil had initially a potential CEC of 25 cmol_c kg⁻¹ which qualified the moderate CEC range (Hazelton and Murphy, 2007). The soil had also relatively high content of exchangeable acidity (2.41 cmol_c kg⁻¹) and Al (1.81 cmol_c kg⁻¹). The percentage of acid saturation and Al saturation were 9.4 and 6.1%, respectively.

The wood ash had CCE and pH values of 71.7% and 12.3, respectively (Table 2). Because of its alkalinity and elevated contents of alkali and alkaline earth elements, wood ash can be utilized to raise the pH of acid soils (Demeyer et al., 2001). The wood ash has relatively higher content of total P compared to the manure. Therefore, wood ash could be used as an alternative

liming material and source of P for acidic soils. Compared to the wood ash, the manure had higher content of total N. This is because the wood lost its N content by the combustion process as the N in the wood is converted to gaseous products.

Effects of the treatments on pH, exchangeable acidity and Al, CEC and available P

The effects of the treatments on the pH, exchangeable acidity, exchangeable Al and available P were very highly significant ($P \leq 0.001$) (Table 3). The soil pH varied from 4.88 to 6.03; exchangeable acidity from 2.22 to 0.12 cmol_c kg⁻¹; exchangeable Al from 1.28 to 0.06 cmol_c kg⁻¹. The Olsen extractable P of the soil varied from 7 to 16.3 mg kg⁻¹ and the Bray I P from 5.7 to 14.0 mg kg⁻¹ (Table 3). The output of the correlation matrix (Table 6) indicated that the pH of the soils was negatively and strongly correlated to the exchangeable acidity ($r = 0.91$, $P \leq 0.01$), exchangeable Al ($r = 0.82$, $P \leq 0.01$) and dithionite citrate bicarbonate extractable Al ($r = 0.89$, $P \leq 0.01$). This result verified that these soil parameters are responsible for the pH change in acid soils. The Olsen extractable P was positively and strongly correlated with Bray I P ($r = 0.97$, $P \leq 0.01$), DPS ($r = 0.87$, $P \leq 0.01$), P_{ox} ($r = 0.88$, $P \leq 0.01$), Al-P ($r = 0.95$, $P \leq 0.01$) and Fe-P (r

Table 3. Effects of applications of the treatments on selected chemical properties.

Treatment	Rate	pH	Ex. AcEx. AICEC			Bray I POlsenP		PAcs	PAIs
			cmol _c kg ⁻¹			mg kg ⁻¹		%	
Control	-	4.89 ⁱ	2.22 ^a	1.28 ^a	25.7	5.7 ^o	7.0 ^p	8.6 ^a	5.0 ^a
	3.5	5.15 ^f	0.85 ^f	0.13 ^e	25.8	5.8 ^o	7.4 ^{op}	3.3 ^f	0.5 ^e
Lime (tons CaCO ₃ ha ⁻¹)	7.0	5.43 ^e	0.35 ^h	0.09 ^e	26.1	6.3 ⁿ	7.7 ^{no}	1.3 ^g	0.3 ^e
	9.2	5.63 ^{bcd}	0.23 ^{ijkl}	0.07 ^e	26.4	6.5 ^m	8.1 ⁿ	0.9 ^{i-l}	0.3 ^e
	11.2	6.03 ^a	0.14 ^{no}	0.07 ^e	26.4	6.8 ^l	8.7 ^m	0.5 ^m	0.3 ^e
	3.5	5.16 ^{fg}	0.78 ^g	0.12 ^e	25.9	9.0 ^h	9.6 ^{kl}	3.0 ^f	0.5 ^e
Wood ash (tons CaCO ₃ ha ⁻¹)	7.0	5.42 ^e	0.35 ^h	0.10 ^e	26.1	9.4 ^g	10.5 ^j	1.3 ^g	0.4 ^e
	9.2	5.66 ^{bc}	0.19 ^{k-o}	0.08 ^e	26.2	9.8 ^f	12.2 ^{fgh}	0.7 ^{j-m}	0.3 ^e
	11.2	5.93 ^a	0.16 ^{mno}	0.06 ^e	26.3	10.2 ^e	13.8 ^d	0.6 ^{lm}	0.2 ^e
	32.5	4.97 ^{hi}	1.90 ^c	0.90 ^b	26.0	7.1 ^k	8.7 ^m	7.3 ^c	3.5 ^b
Manure P (kg ha ⁻¹)	65.0	4.98 ^{hi}	1.74 ^d	0.72 ^c	26.2	7.8 ^j	9.2 ^{lm}	6.6 ^d	2.7 ^c
	130.0	5.03 ^{gh}	1.32 ^e	0.45 ^d	26.1	9.9 ^f	11.4 ⁱ	5.1 ^e	1.7 ^d
	32.5	4.88 ⁱ	2.22 ^a	1.27 ^a	25.9	7.0 ^k	8.7 ^m	8.6 ^a	4.9 ^a
Mineral P (kg ha ⁻¹)	65.0	4.90 ⁱ	2.17 ^{ab}	1.28 ^a	26.2	8.0 ⁱ	9.2 ^{lm}	8.3 ^b	4.9 ^a
	130.0	4.96 ^{hi}	2.13 ^b	1.25 ^a	26.6	10.7 ^d	11.6 ^{ghi}	8.0 ^b	4.7 ^a
	32.5	5.58 ^{cd}	0.27 ^{ij}	0.09 ^e	25.8	7.1 ^k	9.0 ^m	1.0 ^{g-j}	0.3 ^e
Mineral P (kg ha ⁻¹) plus lime (7 tons CaCO ₃ ha ⁻¹)	65.0	5.67 ^{bc}	0.23 ^{j-m}	0.08 ^e	25.7	8.1 ⁱ	10.1 ^{jk}	0.9 ^{i-l}	0.3 ^e
	130.0	5.61 ^{bcd}	0.22 ^{j-m}	0.09 ^e	25.8	10.2 ^d	13.1 ^e	0.9 ^{ijkl}	0.3 ^e
	32.5	5.57 ^{cd}	0.31 ^{hi}	0.09 ^e	26.4	7.0 ^k	8.9 ^m	1.2 ^{ghi}	0.3 ^e
Manure P (kg ha ⁻¹) plus lime (7 tons CaCO ₃ ha ⁻¹)	65.0	5.64 ^{bcd}	0.20 ^{j-n}	0.10 ^e	26.7	7.6 ^j	9.7 ^{kl}	0.8 ^{j-m}	0.4 ^e
	130.0	5.71 ^b	0.12 ^o	0.09 ^e	26.5	8.9 ^h	11.6 ^{hi}	0.5 ^m	0.3 ^e
	32.5	5.53 ^{de}	0.31 ^{hi}	0.08 ^e	25.9	10.6 ^d	12.2 ^{fg}	1.2 ^{gh}	0.3 ^e
Mineral P (kg ha ⁻¹) plus wood ash (7 tons CaCO ₃ ha ⁻¹)	65.0	5.56 ^{cd}	0.24 ^{jk}	0.09 ^e	25.9	11.6 ^c	15.0 ^c	0.9 ^{h-k}	0.3 ^e
	130.0	5.52 ^{de}	0.22 ^{j-m}	0.08 ^e	26.0	14.0 ^a	16.3 ^a	0.8 ^{j-m}	0.3 ^e
	32.5	5.62 ^{bcd}	0.32 ^{hi}	0.07 ^e	25.7	10.3 ^e	12.5 ^f	1.2 ^g	0.3 ^e
Manure P (kg ha ⁻¹) plus wood ash (7 tons CaCO ₃ ha ⁻¹)	65.0	5.64 ^{bcd}	0.20 ^{ijkl}	0.09 ^e	25.8	11.4 ^c	14.4 ^c	0.9 ^{h-l}	0.3 ^e
	130.0	5.62 ^{bcd}	0.15 ^{l-o}	0.07 ^e	26.4	13.4 ^b	15.6 ^b	0.6 ^{klm}	0.3 ^e
	F-test	***	***	***	ns	***	***	***	***
CV (%)		0.95	4.26	13.73	1.54	12.04	1.00	4.90	13.41

Means followed by the same letter within a column are not significantly different at $P > 0.001$; *** = significant at $P \leq 0.001$ using the Duncan's multiple range test; ns = non-significant at $P > 0.05$; CV = coefficient of variation of treatments; Ex. Ac = exchangeable acidity; Ex. Al = exchangeable Al; PAcs = percentage of acid saturation; PAIs = percentage of Al saturation.

= 0.90, $P \leq 0.01$). This result indicated that Al-P and the Fe-P are the most important sources of easily soluble P which are important for plant growth by supplying P to the soil solution. However, Hartikainen (1982) stated that Al-P has a dominant influence over Fe-P in maintaining P concentration in the soil solution in the first place. The (Table 3). This was because both of the lime and the wood ash were applied based on adjusted CCE to have the same CaCO₃ equivalent. Wood ash could thus be highly effective in neutralizing acidified soils. The strong alkalinity of wood ash indicated that it can be an

contribution of Fe-P to maintain P concentration in the soil solution can be expected to become source of available P with decreasing Al-P content.

The lime and wood ash at each respective application levels had significant ($P \leq 0.001$) and similar effects on the soil pH, exchangeable acidity and exchangeable Al alternative to lime either by itself or as a mixture of lime and wood ash for the management of acidity.

Both the lime and wood ash contained cations such as Ca²⁺ and Mg²⁺ to exchange and/or replace H⁺ on the exchange sites and anions such as CO₃²⁻ and OH⁻ to

neutralize the H^+ released from the exchange sites and hydrolyzing Al species to the soil solution (Fageria, 2007). The highest lime rate (11.2 tons $CaCO_3\ ha^{-1}$) significantly ($P \leq 0.001$) increased the pH from 4.89 to 6.03 and reduced both the exchangeable acidity from 2.22 to 0.14 $cmol_c\ kg^{-1}$ and exchangeable Al from 1.28 to 0.07 $cmol_c\ kg^{-1}$. Ayeni et al. (2008) also reported increased soil pH relative to non-ash treated soils. This verified the known truth that applications of liming agents are very effective to alleviate the Al^{3+} and H^+ ions toxicity of acidic soils. The lime rate to raise the pH to 5.5 was highly effective in alleviating Al toxicity problem totally for the soil used for the incubation experiment.

The application of the highest wood ash and lime rates (11.2 tons $CaCO_3\ ha^{-1}$) significantly ($P \leq 0.001$) increased the Bray I extractable P by 79 and 19% and the Olsen extractable P by 97 and 24%, respectively, over the control. The highest available P content associated with the wood ash treated soil was attributed to the fact that wood ash was a source of P in addition to its liming effect (Table 2). An increased available P has been observed previously by the application of ash by different studies (Adetunji, 1997; Nkana et al., 2002; Saarsalmi et al., 2006; Awodun et al., 2007; Insam et al., 2009).

Manure was more effective in the reduction of exchangeable acidity and exchangeable Al compared to its effect in increasing the pH of the soil (Table 3). The reductions in exchangeable Al observed due to application of manure can partially be attributed to its ability to increase the soil pH. This is consistent with other studies (Narambuye and Haynes, 2006; Tang et al., 2007; Opala et al., 2010) which reported an increase in soil pH with a concomitant decrease in exchangeable Al during decomposition of organic residues in soils. An increase in soil pH apparently results in precipitation of exchangeable and soluble Al as insoluble Al hydroxides thus reducing concentration of Al in soil solution.

The application of manure P at 130 $kg\ P\ ha^{-1}$ significantly ($P \leq 0.001$) increased the Bray I extractable P and the Olsen extractable P to 9.9 and 11.4 $mg\ kg^{-1}$, respectively. The mineral P fertilizer application had non-significant effect on the pH, CEC, exchangeable acidity and exchangeable Al compared to the control. The application of mineral P on acidic soils did not have a significant effect on the pH and exchangeable acidity on acidic soils of western Kenya (Opala et al., 2010).

However, the effect of mineral P applications on the Bray I extractable and the Olsen extractable P was significantly ($P \leq 0.001$) higher than that of the control treatment. The application of mineral P at 130 $kg\ P\ ha^{-1}$ significantly ($P \leq 0.001$) increased the Bray I and Olsen P to 10.7 and 11.6 $mg\ kg^{-1}$, respectively. The high available P contents associated with the mineral P treated soils were attributed to the fact that mineral P applied in the form of TSP is a source of soluble P. At the end of the incubation period, the percentage recovery of the applied

manure P and mineral P as Bray I extractable P varied from 8 to 15% and Olsen extractable P from 9 to 16%. A similar result has also been found on the effects of applications of mineral P and manure on the available P contents of acidic soils of western Kenya (Opala et al., 2010).

The application of each manure rate with lime (7.0 tons $CaCO_3\ ha^{-1}$) and wood ash (7.0 tons $CaCO_3\ ha^{-1}$) separately significantly ($P \leq 0.001$) increased the pH and reduced the exchangeable acidity compared to the separate application of the manure, lime and wood ash due to the synergetic effect of the manure and the liming materials to reduce exchangeable acidity and exchangeable Al and increase the pH of acidic soil.

Though the application of manure plus lime did not have significant difference in available P compared with separate application of manure, the application of manure P plus wood ash increased available P compared to the separate manure application. Application of 130 $kg\ manure\ P\ ha^{-1}$ plus wood ash (7.0 tons $CaCO_3\ ha^{-1}$) increased the Bray I P by 135, 36 and 43% and Olsen extractable P by 122, 37 and 48% over the control, 130 $kg\ manure\ P\ ha^{-1}$ and wood ash (7.0 tons $CaCO_3\ ha^{-1}$) treatments, respectively, due to the synergetic effects of the manure and wood ash as sources of soluble P to the soil. Both the application of mineral P fertilizer plus lime and wood ash separately (7.0 tons $CaCO_3\ ha^{-1}$) had a non significant difference in terms of increasing pH, reducing exchangeable Al and exchangeable acidity compared to the lime and wood ash rate (7.0 tons $CaCO_3\ ha^{-1}$).

However, the application of mineral P plus wood ash (7.0 tons $CaCO_3\ ha^{-1}$) gave the highest available P compared to the combined application of mineral P with lime (7.0 tons $CaCO_3\ ha^{-1}$). This is due to the fact that both the mineral P fertilizer and the wood ash were sources of P and made the available P of the incubated soil to be higher. In general, the separate application of the highest manure P and mineral P rates and their combination with 7.0 tons $CaCO_3$ equivalent ha^{-1} lime, all the mineral P and manure P rates plus 7.0 tons $CaCO_3$ equivalent of either lime or wood ash and all the wood ash rates except the lower rate increased the available P content from the lower range to the medium one. None of the treatments had a significant effect on the CEC of the incubated soil compared to the control.

Effects of the treatments on the inorganic P fractions

The forms and distribution of the various inorganic P fractions (Al-P, Fe-P and Ca-P, reds-Fe-P and occl-Al-Fe-P) of the control treatment used for the incubation experiment are shown in Table 4. The distributions of the P fractions were in the following orders: Fe-P > reds-Fe-P > occl-Al-Fe-P > Al-P > Ca-P. The Fe-P was the most

abundant active P form contributing more than 50% of the active P fractions. The abundance of the Fe-P correlated to the high content of free iron oxides in the soil (Table 5). According to Piccolo and Gobena (1986), the low levels of Ca-P compared to Al-P seem to be a consequence of the weathering process of the soils; soil under well drained conditions resulting in the dissolution of the native Ca-P. The high content of Fe-P and Al-P compared to the Ca-P also indicated the advanced stage of weathering of the soil resulting in the dissolution of native Ca-P in acid soils. The degree of P fixation with Al, Fe and Ca was directly related to the intensity of weathering in that when Al and Fe fixation dominated in the soil system, the soil is highly weathered and vice versa (Piccolo and Gobena, 1986). Hence, the present soil is highly weathered with high content of Fe-P active inorganic P fraction.

Previous studies on the different Ethiopian surface soils showed that the active inorganic P fractions were found in the order Ca-P > Fe-P > Al-P (Desta, 1982). Piccolo and Gobena (1986), working on seven Ethiopian soils found that the relative abundance of the inorganic P forms in the profiles was in the order: Fe-P > Al-P > Ca-P > reds-Fe-P. Wakene and Heluf (2003) working on Nitosol under different land use system such as research, farmers and virgin fields found that Fe-P > Al-P > Ca-P in the research field which received high P fertilizer but the order in the other land use system were Fe-P > Ca-P > Al-P.

The effects of the treatments on the inorganic P fractions are shown in Table 4. The result indicated that application of different lime rates had an effect on the Al-P and the Fe-P fractions. The highest lime rate (11.2 tons CaCO₃ ha⁻¹), significantly ($P \leq 0.001$) increased the Al-P from 25 to 39 mg kg⁻¹ and decreased the Fe-P from 157 to 144 mg kg⁻¹. However, application of lime did not have a significant effect on the value of easily soluble P, Ca-P, occluded Al-Fe-P and reds-Fe-P compared to the control treatment except the highest rate which significantly increased the occl-Al-Fe-P. The increase in the Al-P content of the lime treated soils may be due to the release P content from Fe-P pools.

Application of wood ash significantly ($P \leq 0.001$) increased the easily soluble P, Ca-P, Fe-P and occl-Al-Fe-P fractions. The highest wood ash rate (11.2 tons CaCO₃ ha⁻¹) increased the easily soluble P by 389%, Al-P by 132%, Fe-P by 11%, Ca-P by 85% and occl-Al-Fe-P by 16% over the control treatment. This might be due to the phosphate ion released from the wood ash followed by adsorption by the Al and Fe oxides and precipitation as Ca-P. Wood ash did not give significant difference in the value of the reds-Fe-P. In general, wood ash amendment of acid soil was more effective in increasing the value of the active P fractions compared to lime amendment.

It is shown that application of manure P and mineral P

fertilizer at 130 kg P ha⁻¹ significantly increased the easily soluble P by 94 and 94%; Al-P by 40 and 54%; Fe-P by 7 and 8% over the control, respectively. However, the manure and mineral P fertilizer application had no significant effect on the Ca-P, occl-Al-Fe-P and reds-Fe-P except the application of 130 kg mineral P ha⁻¹ treatment which increased significantly the occl-Al-Fe-P fraction. This showed that most of the added P was found to be converted into active Al-P and Fe-P. Chang and Jackson (1958) also observed that application of phosphatic fertilizers to acid soils increases the fixation and transformation of added phosphate into Fe-P. In a study by Sharma et al. (1980) on the transformation of P added at 0, 50, 100 and 150 mg kg⁻¹ to three acid soils of Himachal Pradesh and incubated for 1, 7, 30 and 90 days, it was found that most of the added P was transformed into Al-P, Fe-P and very little to Ca-P fraction at one day interval. The added P which was transformed into Al-P increased (69.5 to 77.8 mg kg⁻¹) up to 7 days and later decreased (77.8 to 65 mg kg⁻¹) slowly with time up to 90 days at all the levels of application. The conversion of added P into Fe-P increased (111.5 to 119.3 mg kg⁻¹) slowly with time up to 90 days and very little (24 to 23 mg kg⁻¹) was changed to Ca-P.

The effect of mineral P application on the different inorganic P fraction was the same as that of the manure treatment in this particular study. Increase in Al-P evident from manure treatment is because, initially, OM forms complex with P fixing metallic cations and reduces fixation of P in soil. The release of P occurs from the reaction products through anion exchange and during later period, due to degradation of organo-metallic complexes, the released P could be precipitated as Al-P. Hence, the action of organic sources is to delay the process of P fixation temporarily and in the long run it favors the precipitation of reaction product (Tomar et al., 1984).

The application of each of the mineral P fertilizers plus lime (7.0 tons CaCO₃ ha⁻¹) significantly increased only the Al-P and the Ca-P compared to the separate application of mineral P fertilizer. The increase in Ca-P in the application of mineral P plus lime (7.0 tons CaCO₃ ha⁻¹) may be due to the fact that lime increased considerably Ca²⁺ in the soil, which reacted with added P and caused precipitation as calcium phosphates. The increase in the fixation of added P by Ca due to liming also reported by Amarasiri and Olsen (1973). The application of each of the manure rates plus lime (7.0 tons CaCO₃ ha⁻¹) increased only the Al-P and occl-Al-Fe-P and decreased the Fe-P compared to the separate manure application. On the other hand, the lower value of Ca-P noticed in the application of manure P plus lime (7.0 tons CaCO₃ ha⁻¹) compared to combined application of mineral P plus the same lime rate because the manure appears to be more effective to form a complex with Ca and Mg which reduces the chance of the reaction of the P with the Ca.

Table 4. Effects of the applications of the treatments on the inorganic P fractions.

Treatment	Rate	mg kg ⁻¹						
		Easily soluble P	Al-PFe-P		Ca-P	Reds – Fe-P	Occl-Al-Fe-P	Sum of fractions
Control	-	0.35 ^e	24.7 ^m	157 ^{jk}	12.8 ^f	67	30.3 ^{kl}	292 ^{lm}
	3.5	0.35 ^e	25.7 ^{lm}	151 ^l	12.8 ^f	67	31.2 ^{g-l}	287 ^m
	7.0	0.35 ^e	27.5 ^{kl}	148 ^{lm}	12.8 ^f	67	31.7 ^{f-l}	288 ^m
	9.2	0.35 ^e	29.0 ^{jk}	147 ^{lm}	12.8 ^f	67	31.9 ^{f-l}	288 ^m
	11.2	0.35 ^e	30.9 ^{hij}	144 ^m	12.8 ^f	67	32.8 ^{e-i}	288 ^m
Lime (tons CaCO ₃ ha ⁻¹)	3.5	0.68 ^d	31.8 ^g	163 ^{ghi}	13.3 ^{ef}	66	31.1 ^{i-l}	308 ^j
	7.0	1.03 ^c	43.9 ^e	168 ^{ef}	14.7 ^e	67	31.2 ^{g-l}	325 ^h
	9.2	1.34 ^b	51.7 ^d	170 ^{de}	18.5 ^d	67	32.1 ^{f-l}	341 ^g
	11.2	1.71 ^a	57.3 ^{bc}	174 ^{cd}	23.7 ^b	67	35.3 ^{cd}	359 ^d
	32.5	0.35 ^a	28.0 ^k	158 ^{jk}	12.8 ^f	67	30.4 ^{kl}	296 ^{kl}
Wood ash (tons CaCO ₃ ha ⁻¹)	65.0	0.52 ^{de}	29.3 ^{ijk}	161 ^{hij}	12.8 ^f	67	30.3 ^{kl}	301 ^k
	130.0	0.68 ^d	34.8 ^g	168 ^{efg}	12.8 ^f	67	31.1 ^{h-l}	314 ⁱ
	32.5	0.35 ^e	28.7 ^{jk}	159 ^{ijk}	12.7 ^f	68	32.0 ^{f-l}	301 ^k
Manure P (kg ha ⁻¹)	65.0	0.52 ^{de}	31.5 ^{hi}	164 ^{ghi}	12.8 ^f	69	32.1 ^{f-l}	309 ^j
	130.0	0.68 ^d	38.1 ^f	169 ^e	12.8 ^f	69	33.5 ^{def}	323 ^h
	32.5	0.35 ^e	34.3 ^g	159 ^{ijk}	18.5 ^d	67	32.5 ^{e-j}	312 ^{ij}
Mineral P (kg ha ⁻¹) plus lime (7 tons CaCO ₃ ha ⁻¹)	65.0	0.35 ^e	36.9 ^f	164 ^{igh}	20.1 ^c	67	32.4 ^{f-k}	321 ^h
	130.0	0.35 ^e	43.7 ^e	177 ^c	24.1 ^{ab}	68	33.8 ^{e-i}	345 ^{fg}
	32.5	0.35 ^e	30.7 ^{hij}	149 ^{lm}	12.8 ^f	69	32.0 ^{f-l}	294 ^{lm}
Manure P (kg ha ⁻¹) plus lime (7 tons CaCO ₃ ha ⁻¹)	65.0	0.52 ^{de}	32.8 ^{gh}	150 ^{lm}	12.8 ^f	68	34.4 ^{cde}	298 ^{kl}
	130.0	0.68 ^d	37.3 ^f	157 ^k	12.7 ^f	68	35.8 ^{bc}	311 ^{ij}
	32.5	1.04 ^c	52.4 ^d	177 ^c	18.5 ^d	68	33.2 ^{e-h}	350 ^{ef}
Mineral P (kg ha ⁻¹) plus wood ash (7 tons CaCO ₃ ha ⁻¹)	65.0	1.36 ^b	57.4 ^{bc}	186 ^b	20.6 ^c	69	35.4 ^{cd}	369 ^c
	130.0	1.38 ^b	64.1 ^a	192 ^a	24.1 ^{ab}	67	37.6 ^{ab}	386 ^a
	32.5	1.04 ^c	50.9 ^d	178 ^c	20.1 ^c	68	33.3 ^{efg}	351 ^e
Manure P (kg ha ⁻¹) plus wood ash (7 tons CaCO ₃ ha ⁻¹)	65.0	1.04 ^c	55.8 ^c	182 ^b	22.7 ^b	67	36.4 ^{bc}	366 ^c
	130.0	1.22 ^{bc}	59.3 ^b	187 ^b	25.3 ^a	67	38.9 ^a	379 ^b
	F-test	***	***	***	***	ns	***	***
CV (%)		12.04	2.57	1.21	4.21	1.97	2.61	0.72

Means followed by the same letter within a column are not significantly different at P > 0.001; *** = significant at P ≤ 0.001 using Duncan's multiple range test; ns = non-significant at P > 0.05; CV = coefficient of variation; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; reds-Fe-P = reductant soluble Fe-P; occl-Al-Fe-P = occluded Al-Fe-P.

Similar results were reported by Srivastava et al. (1969) who observed decrease in content of Ca-P and increase in Al-P with the application of farm yard manure and compost.

Due to the synergetic effect of the manure and wood ash and mineral P fertilizer and wood ash as a source of phosphate ion to be sorbed by Al, Fe and Ca of the soil, manure plus wood ash (7.0 tons CaCO₃ ha⁻¹) and mineral

P fertilizer with wood ash (7.0 tons CaCO₃ ha⁻¹) significantly (P ≤ 0.001) increased the easily soluble P, the active Al-P, Fe-P and Ca-P fractions and the occl-Al-Fe-P compared to the separate application of manure P, mineral P, wood ash (7.0 tons CaCO₃ ha⁻¹) and the control treatments. For instance, both the manure and mineral P rates of 130 kg P ha⁻¹ plus wood ash (7.0 tons CaCO₃ ha⁻¹) cause a significant increase in easily soluble

Table 5. Effects of applications of the treatments on Al_{ox}, Fe_{ox}, P_{ox}, DPS, Al_d and Fe_d.

Treatment	Rate	Al _{ox}	Fe _{ox}	P _{ox}	PSC	Al _{ox} -P ^a	Fe _{ox} -P ^b	P _{ox}	Al _d	Fe _d
		(mmol kg ⁻¹)				(DPS, %)			(mmol kg ⁻¹)	
Control	-	139.4 ^{c-f}	85.6 ^{bc}	7.6 ⁱ	225.0 ^{def}	0.57 ^q	5.91 ^{hij}	3.4 ^l	95 ^a	358 ^a
	3.5	139.3 ^{c-f}	84.0 ^{de}	7.8 ^{hi}	223.3 ^{efg}	0.60 ^{pq}	5.78 ^{ijk}	3.5 ^{kl}	92 ^{cd}	351 ^{c-h}
	7.0	139.0 ^{d-h}	83.6 ^{def}	7.8 ^{hi}	222.6 ^{f-i}	0.64 ^{op}	5.72 ^{jk}	3.5 ^{kl}	89 ^{efg}	343 ^{jk}
	9.2	138.3 ^{d-i}	82.4 ^{ef}	7.8 ^{hi}	220.7 ^{h-k}	0.68 ^{mno}	5.77 ^{ijk}	3.6 ^{kl}	88 ^{fg}	345 ^{ijk}
Lime (tons CaCO ₃ ha ⁻¹)	11.2	137.5 ^{g-k}	82.4 ^f	7.8 ^{hi}	219.9 ^{jk}	0.72 ^{klm}	5.69 ^{jk}	3.6 ^{kl}	88 ^g	342 ^k
	3.5	139.3 ^{c-g}	84.2 ^{de}	8.2 ^{ghi}	223.5 ^{efg}	0.78 ^{hij}	6.25 ^{fg}	3.7 ^{kl}	93 ^{bc}	355 ^{bc}
	7.0	138.5 ^{d-h}	83.0 ^{ef}	8.3 ^{gh}	221.5 ^{g-j}	1.02 ^e	6.53 ^{cd}	3.8 ^{ijk}	90 ^{de}	346 ^{h-k}
	9.2	137.9 ^{e-j}	82.6 ^{ef}	8.7 ^{a-g}	221.5 ^{g-j}	1.21 ^d	6.58 ^{cd}	4.0 ^{e-j}	91 ^{de}	347 ^{g-k}
Wood ash (tons CaCO ₃ ha ⁻¹)	11.2	137.4 ^{g-k}	81.7 ^f	9.4 ^{abc}	219.0 ^{jk}	1.35 ^c	6.86 ^b	4.3 ^{a-d}	90 ^{de}	345 ^{ijk}
	32.5	136.4 ^{i-m}	83.6 ^{def}	7.8 ^{hi}	219.0 ^{jk}	0.66 ^{no}	6.11 ^{gh}	3.6 ^{kl}	94 ^{ab}	352 ^{b-e}
	65.0	135.7 ^{no}	83.4 ^{def}	8.6 ^{fg}	219.4 ^{jk}	0.69 ^{lmn}	6.21 ^g	3.9 ^{f-j}	94 ^{ab}	353 ^{b-e}
	130.0	134.8 ^o	83.8 ^{def}	9.1 ^{c-f}	218.6 ^k	0.83 ^{gh}	6.45 ^{def}	4.2 ^{a-f}	94 ^{ab}	352 ^{b-f}
Manure P (kg ha ⁻¹)	32.5	138.1 ^{e-j}	84.1 ^{de}	8.2 ^{ghi}	222.2 ^{fgh}	0.67 ^{no}	6.06 ^{gh}	3.7 ^{kl}	95 ^a	355 ^{abc}
	65.0	137.0 ^{j-m}	82.6 ^{ef}	8.7 ^{a-g}	221.2 ^{g-k}	0.74 ^{jkl}	6.27 ^{efg}	4.0 ^{e-j}	94 ^{ab}	356 ^{ab}
	130.0	136.2 ^{j-m}	83.1 ^{ef}	9.6 ^{abc}	219.6 ^{jk}	0.90 ^f	6.53 ^{cd}	4.4 ^{abc}	94 ^{ab}	352 ^{b-f}
Mineral P (kg ha ⁻¹)	32.5	138.9 ^{efg}	89.0 ^a	8.1 ^{ghi}	227.0 ^{ef}	0.79 ^{hi}	5.78 ^{ijk}	3.6 ^{kl}	90 ^{de}	351 ^{b-f}
	65.0	140.1 ^{a-c}	88.9 ^a	8.7 ^{efg}	229.0 ^{ab}	0.85 ^g	5.97 ^{hi}	3.8 ^{g-k}	90 ^{de}	349 ^{d-i}
	130.0	141.0 ^a	88.1 ^a	9.2 ^{c-f}	229.1 ^{ab}	1.00 ^e	6.47 ^{de}	4.1 ^{d-i}	90 ^{ef}	350 ^{d-i}
Mineral P (kg ha ⁻¹) plus lime (7 tons CaCO ₃ ha ⁻¹)	32.5	138.8 ^{e-h}	88.2 ^a	8.3 ^{gh}	227.0 ^{a-d}	0.71 ^{k-n}	5.41 ^l	3.7 ^{ijkl}	90 ^{de}	353 ^{bc}
	65.0	140.1 ^{a-d}	88.6 ^a	9.1 ^{c-f}	228.6 ^{ab}	0.76 ^{ijk}	5.40 ^l	4.0 ^{e-j}	90 ^{def}	352 ^{b-f}
	130.0	140.7 ^{ab}	89.0 ^a	9.4 ^{bcd}	229.7 ^a	0.86 ^{fg}	5.68 ^k	4.1 ^{b-h}	89 ^{efg}	351 ^{c-h}
Mineral P (kg ha ⁻¹) plus wood ash (7 tons CaCO ₃ ha ⁻¹)	32.5	139.2 ^{c-f}	87.2 ^{ab}	9.3 ^{b-e}	226.4 ^{bcd}	1.21 ^d	6.58 ^{cd}	4.1 ^{b-g}	90 ^{def}	347 ^{e-j}
	65.0	139.8 ^{b-e}	88.1 ^a	9.7 ^{abc}	228.0 ^{abc}	1.32 ^c	6.80 ^b	4.3 ^{a-e}	90 ^{de}	348 ^{f-j}
	130.0	139.8 ^{b-e}	87.1 ^{ab}	10.1 ^a	227.0 ^{bcd}	1.48 ^a	7.10 ^a	4.5 ^a	89 ^{ef}	346 ^{h-k}
Manure P (kg ha ⁻¹) plus wood ash (7 tons CaCO ₃ ha ⁻¹)	32.5	139.0 ^{d-g}	87.6 ^{ab}	9.2 ^{c-f}	227.0 ^{bcd}	1.18 ^d	6.54 ^{cd}	4.1 ^{b-h}	88 ^{efg}	353 ^{b-e}
	65.0	137.7 ^{h-k}	87.8 ^{ab}	9.5 ^{abc}	226.6 ^{cde}	1.31 ^c	6.70 ^{bc}	4.2 ^{a-f}	89 ^{efg}	351 ^{b-g}
	130.0	136.7 ^{k-m}	88.5 ^a	9.9 ^{ab}	225.2 ^{bcd}	1.40 ^b	6.80 ^b	8.8 ^{ab}	88 ^{fg}	346 ^{h-k}
F-test		***	***	***	***	***	***	***	***	***
CV (%)		0.46	0.52	3.27	0.65	2.55	1.54	3.53	0.81	0.59

Means followed by the same letter within a column are not significantly different at $P > 0.001$; *** = significant at $P \leq 0.001$ using Duncan's multiple range test; CV = coefficient of variation; Al_{ox}, Fe_{ox} and P_{ox} = oxalate extractable Al, Fe and P, respectively; Al_d and Fe_d = dithionite citrate bicarbonate extractable Al and Fe, respectively; PSC = P sorption capacity; ^a and ^b = DPS of the active Al-P and Fe-P fractions with respect to Al_{ox} and Fe_{ox}, respectively.

P by 248 and 294%; Al-P by 140 and 160%; Fe-P by 19 and 22%; Ca-P by 98 and 88%; occl-Al-Fe-P by 28 and 24%, respectively, compared to the control treatment. The soils used in this study contained free Al and Fe oxides which are responsible for the high contents of occl-Al-Fe-P in the applications of manure P and mineral P rates plus wood ash. The non-significant difference in the reds-Fe-P among the treatments was observed in this study. According to Chang and Jackson (1957), the reds-

Fe-P is the Fe-oxide precipitate formed on the surface of Fe and Al-oxides during weathering. This may result in slow transformation between the added P and the native reds-Fe-P. However, application of wood ash to soil must be controlled to maximize its benefit and prevent adverse effects on the environment or future fertility/sustainability of the fields to which they are applied.

The result indicated in Table 4 verified that most of the applied P was converted into the active inorganic P

Table 6. Correlation coefficients (r) among selected soil chemical properties.

Property	BP	OLP	DPS	P _{ox}	Al-P	Fe-P	pH	Ex. Al	Ex. Ac	Al _{ox}	Fe _{ox}	Al _d
OLP	0.97**											
DPS	0.87**	0.86**										
P _{ox}	0.88**	0.88**	0.98**									
Al-P	0.92**	0.95**	0.78**	0.80**								
Fe-P	0.92**	0.90**	0.76**	0.77**	0.89**							
pH	0.26	0.40**	0.21**	0.27*	0.49**	0.11						
Ex. Al	-0.27*	-0.35**	-0.14	-0.21	-0.40**	-0.14	-0.82**					
Ex. Ac	-0.32*	-0.42**	-0.20	-0.28*	-0.51**	-0.17	-0.91**	0.97**				
Al _{ox}	-0.04	0.04	-0.15	0.01	0.10	-0.01	0.39**	-0.43**	-0.49**			
Fe _{ox}	0.30*	0.36**	0.22	0.39**	-0.30*	0.38*	0.25	-0.28*	-0.34**	0.52**		
Al _d	-0.27*	-0.36**	-0.17	-0.24	-0.45*	-0.13	-0.89**	0.82**	0.90**	-0.43**	-0.27*	
Fe _d	-0.25	-0.29*	-0.13	-0.12	-0.39**	-0.12	0.64**	0.59**	0.64**	-0.09	0.18	0.68**

*, ** = significant at 0.05 and 0.01 probability levels, respectively; BP = Bray I P; OLP = Olsen P; DPS = degree of P saturation; Ex. Ac and Ex. Al= exchangeable acidity and Al, respectively.

fractions in which the percentage of recovery of applied P as Al-P dominated the Fe-P and Ca-P. The effect of application of mineral P fertilizer on the recovery of applied P into the inorganic P fractions such as Al-P and Fe-P was higher than application of manure P. This showed that application of mineral P fertilizers to highly weathered acid soils with high content of Al and Fe oxides and hydroxides resulted in the strong adsorption of the P into Al-P and Fe-P which in turn resulted in the low content of soluble P available to plant growth. The percentage recovery of the applied manure P as Al-P and Fe-P ranged from 17 to 24%, and 10 to 21%, respectively, whereas the percentage recovery of the applied mineral P as Al-P and Fe-P ranged from 26 to 29% and 16 to 24%, respectively. This can be further verified by the result of the lower percentage recovery of the applied P as easily soluble P due to the applications of the treatments. The percentage recoveries of the available P which were extracted by the Bray I and Olsen P methods were ranging from 7 to 14% and 8 to 15%, respectively.

Effects of the treatments on the Al_{ox}, Fe_{ox}, P_{ox}, DPS, Al_d and Fe_d

The soil used for the incubation experiment was very rich in oxalate extractable Al and Fe and dithionite citrate bicarbonate extractable Al and Fe (Table 5). Piccolo and Gobena (1986) working on seven Ethiopian soils found that the Fe_d varied between 10 to 525 mmol kg⁻¹. Therefore, the soil used for the incubation is rich in oxides and hydroxides of Fe. The low pH and high content of the Al and Fe oxides and hydroxides of the soil results in a significant P fixation and precipitation of applied and native P of the soil as Al-P and Fe-P.

The data in Table 5 illustrate the difference between the P_{ox}, Al_{ox}, Fe_{ox}, PSC and DPS values of the soils as the result of the treatments used in the incubation experiment. The P_{ox} values of the incubated soils varied from 7.6 to 9.9 mmol kg⁻¹. The sum of the two oxides (Al_{ox} + Fe_{ox}), an important estimate of the PSC of the soil, was significantly influenced by the application of the treatments. The maximum increment (2.1%) in the value of the PSC was recorded at the application of 130 kg manure P ha⁻¹ plus lime (7.0 tons CaCO₃ ha⁻¹) compared to the control treatment. The DPS was significantly influenced by the different treatments used for the incubation. The DPS values varied from 3.4% in the control to 4.5% in 130 kg mineral P ha⁻¹ plus wood ash (7.0 tons CaCO₃ ha⁻¹) treatment.

Lime application did not have any significant effect on the P_{ox} and DPS values in which the maximum increment in P_{ox} (3.0%) and DPS (5.4%) was observed at the highest lime rate (11.2 tons CaCO₃ ha⁻¹) compared to the control treatment but the values increased numerically with increasing the lime levels. The DPS of Al_{ox} is higher than that of Fe_{ox} in all lime treated soils. This may be due to the transfer of the phosphate ion from Fe to Al (Table 4). Wood ash significantly increased the P_{ox} and DPS value of the soil compared to the control and the lime treated soils. The maximum increment in P_{ox} (19.8%) and DPS (22.0%) was recorded at the highest wood ash rate (11.2 tons CaCO₃ ha⁻¹) compared to the control. The high content of P in the wood ash made the P_{ox} and DPS higher than in lime treated soils. This may be due to the fact the P available in the wood ash was immediately fixed by the amorphous Al_{ox} and Fe_{ox} present in the soil which in turn increased the DPS.

Application of manure P, mineral P, manure P with lime, mineral P with lime, manure plus wood ash and mineral P plus wood ash significantly (P ≤ 0.001)

increased the values of P_{ox} and DPS values. The maximum increment of P_{ox} (24.9%) and DPS (24.2%) were recorded at the application of 130 kg mineral P ha^{-1} plus wood ash (7.0 tons $CaCO_3 ha^{-1}$) compared to the control treatment. The DPS with respect to Al_{ox} -P ranged from 0.57 to 1.48% and Fe_{ox} -P ranged from 5.91 to 7.10% where the lowest and the highest DPS were observed at the control and the application of 130 kg mineral P ha^{-1} plus wood ash (7.0 tons $CaCO_3 ha^{-1}$), respectively. This result showed that more of Fe_{ox} are occupied by P as compared to Al_{ox} . In line with this, the percentage recovery of the applied P as Al-P was greater than Fe-P. This clearly indicated that Al_{ox} had high tendency of P fixation than that of Fe_{ox} . All the treatments resulted in the reduction of the Al_d and Fe_d compared to the control treatment. The reduction for the value of Al_d varied from 0.1 to 7.5% and Fe_d from 0.6 to 4.4%.

The reductions in Al_{ox} , Fe_{ox} , Al_d and Fe_d contents as the result of manure and mineral P application may be due the fixation of Al and Fe in the form of Al-P and Fe-P. Both the amorphous and crystalline Al and Fe are the potential P fixation sites and their role can be explained as follow. Upon hydrolysis, the amorphous and crystalline forms of Al and Fe expose much larger surface area where high affinity for fixation of P takes place on protonated sites. The fixation could also take place by the hydroxyl displacement by $H_2PO_4^-$ ions from the surface of hydrous oxides of Al and Fe. Similar findings were also made in Kaistha et al. (1997). The complex formation of Al and Fe by the organic acids produced as the result of mineralization of the manure may compute with the citrate ion to extract Al and Fe. This may result in the reduction of the amount of Fe and Al to be extracted by citrate dithionite bicarbonate.

Conclusion

The result of this study showed that applications of lime and wood ash to obtain a target pH of 6.5 significantly increased the pH of the soil, decreased the exchangeable acidity and exchangeable Al almost equally. However, wood ash performed better in increasing the available P, the easily soluble P, Al-P, Fe-P, P_{ox} , and DPS compared to lime. Application of manure P and mineral P plus lime and wood ash at target pH value of 5.5 performed very well in alleviating acidity related problems compared to the corresponding separate applications. Mineral P application with wood ash gave the highest available P, easily soluble P fraction, P_{ox} , and DPS. Application of manure P plus wood ash also resulted in comparable values.

Applications of manure and other organic residues to soils in the highlands of Ethiopia, where there is acidity and P fixation problems, could result in improved soil and fertilizer P use efficiency by crops partly as a consequence of increasing availability P and pH,

reducing exchangeable acidity and Al and supplying N to the soil. Therefore, knowledge of the extent to which applications of wood ash and organic residues to reduce lime and fertilizer P requirement is needed so that integrated soil fertility management programmes can be planned. In line with this, use of wood ash for soil acidity management must be controlled to maximize its benefits and prevent adverse effects on the environment or future fertility/sustainability of the farms to which they are applied.

Conflict of Interests

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

This work was supported by Center for International Mobility (CIMO), Finland, the University of Helsinki Future Funds (Tulevaisuusrahasto) and Ethiopian Ministry of Education.

REFERENCES

- Adetunji MT (1997). Organic residue management and nutrient cycling. *Agro-ecosyst.* 47:189-195.
- Amarasiri SL, Olsen SR (1973). Liming in an acid tropical soils. *Soil Sci. Soc. Am. Proc.* 37:716-721.
- Awodun MA, Otani MS, Ojeniyi SO (2007). Effect of sawdust ash plus urea on maize performance and nutrient status. *Asian J. Agric. Res.* 12:27-30.
- Ayeni LS, Adetunji MT, Ojeniyi SO (2008). Comparative nutrient release from Cocoa pod ash, poultry manure and N.P.K 20:10:10 fertilizer and their nutrient combinations-Incubation study. *Nig. J. Soil Sci.* 18:114-123.
- Bray HR, Kurtz LT (1945). Determination of organic and available forms of phosphorus in soils. *Soil Sci.* 9:39-46.
- Chang SC, Jackson ML (1957). Fractionation of soil phosphorus. *Soil Sci.* 84:133-144.
- Chang SC, Jackson ML (1958). Soil phosphorus fractions in some representative soils. *Soil Sci.* 9:109-119.
- Chapman HD (1965). Cation exchange capacity by ammonium saturation. In: C.A. Black (ed.). *Methods of Soil Analysis*. Agronomy Part II, No. 9. American Society of Agronomy, Madison, Wisconsin, USA. pp. 891-901.
- Chopra SH, Kanwar JS (1976). *Analytical Agricultural Chemistry*. Kalyani Publisher Ludhiana, New Delhi, India.
- Cottenie A (1980). Soil and plant testing as a basis of fertilizer recommendations. *FAO soil bulletin* 38/2. Food and Agriculture Organization of the United Nations, Rome.
- Day PR (1965). Hydrometer method of particle size analysis. In: C.A. Black (ed.). *Methods of soil analysis*. Agronomy Part I, No. 9. American Society of Agronomy, Madison, Wisconsin, USA. pp. 562-563.
- Demeyer A, Nkana JCV, Verloo MG (2001). Characteristics potential negative impacts to the environment of wood ash and influence on soil properties and nutrient uptake: An overview. *Biores. Technol.* 77:287-295.
- Desta B (1982). Diagnosis of phosphorous deficiency in Ethiopian soils. *Soil Science Bulletin*, No. 3, Addis Ababa, Ethiopia: Institute of Agricultural Research.
- Erich MS, Fitzgerald CB, Porter GA (2002). The effect of amendments

- on phosphorus chemistry in a potato cropping system. *Agric. Ecosyst. Environ.* 88:79-88.
- Fageria NK, Baliger VC, Zobel RW (2007). Yield, nutrient uptake and soil chemical properties as influenced by liming and boron application in a no-tillage system. *Commun. Soil Sci. Plant Anal.* 38:1637-1652.
- Fageria NK (2009). *The Use of Nutrients in Crop Plants*. CRC Press.
- Fairhurst TR, Lefroy R, Mutert E, Batijes N (1999). The importance, distribution and causes of phosphorus deficiency as a constraint to crop production in the tropics. *Agroforest. Forum* 9:2-8.
- FAO (Food and Agriculture Organization) (1981). *Soils map of the world 1:5,000,000*. FAO/UNESCO, Rome, Italy.
- Hartikainen H (1982). Water soluble phosphorus in Finnish mineral soils and its dependence on soil properties. *J. Sci. Agri. Soc. Finl.* 54:204-209.
- Hartikainen H, Rasa K, Withers PJA (2010). Phosphorus exchange properties of European soils and sediments derived from them. *Eur. J. Soil Sci.* 61:1033-1042.
- Haug A (1983). Molecular aspects of aluminium toxicity. *CRC Crit. Rev. Plant Sci.* 1:345-373.
- Hazelton P, Murphy B (2007). *Interpreting Soil Test Results: What do all the numbers mean?* 2nd ed. CSIRO Publishing.
- Insam H, Franke-Whittle IH, Knapp BA, Plank R (2009). Use of wood ash and anaerobic sludge for grassland fertilization: Effects on plants and microbes. *Die Bodenkultur* 60:39-51.
- Iyamuremye F, Dick RP (1996). Organic amendments and phosphorus sorption by soils. *Adv. Agron.* 56:139-185.
- Jackson ML (1967). *Soil Chemical Analysis*. Prentice Hall Pvt. Ltd., New Delhi.
- Jamison VC, Weaver HH, Reed IF (1950). A hammer-driven soil core sampler. *Soil Sci.* 69:487-496.
- Jones JB (2003). *Agronomic Handbook: Management of Crops, Soils, and Their Fertility*. CRC Press LLC, Boca Raton, FL, USA. P 482.
- Kaistha BP, Sharma KP, Sharma RP (1997). Influence of soil components on phosphorous fixing capacity of some Alfisols of Himachal Pradesh. *J. Indian Soc. Soil Sci.* 45:261-264.
- Kisinyo PO, Othieno CO, Gudu SO, Okalebo JR, Opala PA, Maghanga JK, Ngetich WK, Agalo JJ, Opile RW, Kisinyo JA, Ogolay BO (2013). Phosphate sorption and lime requirements of maize growing acidic soils of Kenya. *Sustain. Agric. Res.* 2:116-123.
- Lupwayi NZ, Haque I (1996). Phosphorous: A prerequisite for increased productivity of forage and browse/free legumes in the Ethiopian highlands. In: *Proceedings of the Second Conference of the Ethiopian Society of Soil Science*, 23-24 Sept., 1993, Addis Ababa, Ethiopia.
- Mehra OP, Jackson ML (1960). Iron oxide removal from soils and clays by a dithionate-citrate system buffered with sodium bicarbonate. *Clays and Clay Minerals* 7:317-327.
- Mweta DE, Akinnifesi FK, Saka JDK, Makumba W, Chokocho N (2007). Green manure from prunings and mineral fertilizer affect phosphorous adsorption and uptake by maize crop in a gliricidia-maize intercropping. *Sci. Res. Essays* 2:446-453.
- Narambuye FX, Haynes RJ (2006). Short-term effects of three animal manures on soil pH and aluminum solubility. *Aust. J. Soil Res.* 44:515-521.
- Niskanen R (1989). Extractable aluminum, iron and manganese in mineral soils. I. Dependence of extractability on the pH of oxalate, pyrophosphate and EDTA extratants. *J. Agri. Sci. Finland* 61:73-77.
- Nkana JCV, Demeyer A, Verloo MG (2002). Effect of wood ash application on soil solution chemistry of tropical acid soils: incubation study. *Biores. Technol.* 85:323-325.
- NWRMSA (North Western Regional Metrological Service Agency) (2010). Debre Tabor weather station rain fall and temperature data. NWRMSA, Bahir Dar, Ethiopia.
- Olsen SR, Watenabe VC, Dean LA (1954). Estimate of available phosphorous in soil by extraction with sodium bicarbonate. *USDA Circular*. No. 939.
- Opala PA, Okalebo JR, Othieno CO, Kisinyo P (2010). Effects of organic and inorganic phosphorus sources on maize yields in acid soils of western Kenya. *Nutr. Cycl. Agroecosyst.* 86:317-329.
- Opara-Nadi OA (1988). Liming and organic matter interaction in two Nigerian Ultisols. Effect on soil pH, organic carbon and early growth of maize (*Zea mays* L). *Proceedings of the 16th annual conference of Soil Science Society of Nigeria*. Minna, Niger state. Nov 27-30th 1988. pp. 177-198.
- Piccolo A, Gobena H (1986). Phosphorus status of some Ethiopian soils. *Trop. Agric.* 63:137-142.
- Regional Office of Planning for Northwestern Ethiopia (1985). *Regional Atlas of Northwest Ethiopia*, Bahir Dar, Ethiopia.
- Rowell DL (1994). *Soil Science: Method and Applications*. Addison Wesley Longman Limited, England.
- Saarsalmi A, Kukkola M, Moilanen M, Arola M (2006). Long-term effect of ash and N fertilization on stand growth, tree nutrient status and soil chemistry in a Scots pine stand forest. *For. Ecol. Manage.* 235:116-128.
- Sanchez PA, Uehara G (1980). Management considerations for acid soils with high phosphorus fixation capacity. In: Khasawneh FE, Sample EC, Kamprath EJ (eds). *The Role of Phosphorus in Agriculture*. American Society of Agronomy. Madison, Wisconsin, USA. pp. 263-310.
- SAS (Statistical Analysis System) Institute (2004). *SAS/STAT user's guide*. Proprietary software version 9.00. SAS Institute, Inc., Cary, NC.
- Sharma PK, Verma SP, Bhumala DR (1980). Transformation of added phosphorus into inorganic phosphorus fractions in some acid soils of Himachal Pradesh. *J. Indian Soc. Soil Sci.* 28:450-453.
- Shiferaw B (2004). Soil phosphorous fractions influenced by different cropping system in Andosols and Nitisols in Kambata-Tenbaro and Wolaita Zones, SNNPRS, Ethiopia. MSc Thesis, Alemaya University.
- Srivastava OP, Manna GS, Bhatia LS (1969). Effect of organic manures on the availability of native and applied phosphorus. *J. Res. Punjab Agric. University* 6:620-625.
- Tang Y, Zhang H, Schroder JL, Payton ME, Zhou D (2007). Animal manure reduces aluminum toxicity in acid soils. *Soil Sci. Soc. Am. J.* 71:1699-1707.
- Tekalign M, Haque I (1987). Phosphorous status of some Ethiopia soils. Sorption characteristics. *Plant Soil* 102:261-266.
- Tomar NK, Khanna SS, Gupta AP (1984). Transformation of phosphates varying in citrate and water solubility in a calcareous soil after incubation with cattle dung. *J. Indian Soc. Soil Sci.* 32:421-426.
- Wakene N, Heluf G (2003). Forms of phosphorus and status of available micronutrients under different land-use systems of Alfisols in Bako area of Ethiopia. *Ethiop. J. Nat. Resour.* 5:17-37.
- Walker TW, Syers JK (1976). The fate of phosphorus during pedogenesis. *Geoderma* 15:1-19.
- Wassie H, Shiferaw B (2009). Mitigation of soil acidity and fertility decline challenges for sustainable livelihood improvement: research findings from southern region of Ethiopia and its policy implications. *Awassa Agricultural Research Institute*.
- WOARD (Woreda Office of Agriculture and Rural Development) (2005). *Descriptive data on biophysical and socio-economic characteristics of Farta Woreda*. Unpublished Document, Debre Tabor, Ethiopia.