

Soil Chemical Properties as affected by Tillage method, Phosphorus and Lime application

ABSTRACT

Continuous land degradation and soil acidity are some of the major causes of below optimal crop yields in Kenya. Sustainable crop production therefore calls for efficient soil health management strategies. Field experiments were carried out at Waruhiu Farmers Training Centre, Kiambu for two seasons to evaluate the effects of tillage methods, phosphorus and lime application on selected properties of acid soils. Ploughing, strip tillage and hand hoe tillage methods and, DAP + lime (DAPL), TSP + lime (LP), TSP (P) were evaluated. Burnt lime at 3.2 tones ha⁻¹ rate was used as lime source while 52kg P ha⁻¹ was used as Phosphorus source. Obtained data indicated that the soils were strongly acidic with high exchangeable Al³⁺ and Al saturation, low cation Exchange capacity (CEC) and available P. Combination of Ploughing, lime and phosphorus in form of TSP significantly ($P \leq 0.05$) led to > 38% increase of soil pH, >75% extractable P, 51% exchangeable Ca, >60% CEC, 54% Exchangeable Mg and reduced Al concentrations by >83% compared to the control. Similarly, combination of ploughing, DAP and lime significantly ($P \leq 0.05$) increased CEC by 42% and available P by 81% compared to control. DAPL was observed to significantly ($P \leq 0.05$) promote higher levels of exchangeable Al Compared to control and LP in both seasons. Plough DAPL also increased available P by 49% compared to strip DAPL. Strip LP significantly increased Exchangeable Ca by 46% compared to control. Sole tillage methods did not significantly affect soil properties. It can, be concluded that integrating ploughing with either DAPL or LP improves the selected acid soil properties. There is however need for long term studies to understand long term effects of the fertilizer- lime -tillage methods interaction on soil acidity management.

Key words: Acid soils, phosphorus, lime, tillage, fertilizer

1.0 INTRODUCTION

Acid soils occupy approximately 13% of the Kenyan land area [1] and most of them are found in the highland east and west of the Rift Valley [2]. The soil acidity is attributed to either clay mineralogy, leaching of bases due to high rainfall, presence of Al, Fe and Si-oxides and oxyhydroxides, and/ or continuous use of acid forming fertilizers [3; 2]. Most of the acid soils in Kenya were developed from non-calcareous parent materials such as syenites, phololites, trachytes, olivines, older basic tuffs and nepholites which are acidic in nature [3]. The predominant clay minerals in the highlands of Kenya are kaolinite, gibbsite, goethite, Al and Fe oxides [2; 4; 5], which are the products of extensive weathering of the parent materials.

According to [6] soils of the highlands east of the Rift Valley are strongly acidic ($\text{pH} < 5$), have high exchangeable Al^{3+} , and high % Al saturations attributed to extensive weathering and leaching of the bases. The exchangeable Al^{3+} is usually $> 2.0 \text{ cmol kg}^{-1}$ and Al saturation $> 20\%$. This high level of exchangeable Al^{3+} is considered by Landon [7] to be too high for many crops, and such Al saturation level cannot be tolerated by many maize germplasms grown in Kenya [8]. The P sorption capacities of the soils have been reported to vary from $434\text{-}208 \text{ mg kg}^{-1}$ soil [6; 9; 10]. This leads to low recovery of applied P, hence low availability of soil P ($< 5 \text{ mg P kg}^{-1}$) in most soils for crop and soil biota uptake.

The form in which applied P accumulates in soils after regular fertilization depends on the amounts applied, amounts exported, soil type and soil management practices [11; 12]. Practices like liming and tillage have been documented to play a significant role in soil P management. According to Robson and Taylor [13], tillage practices alter nutrients via 3 processes: (i) mixing nutrients through the soil and altering their availability to crops (ii) changing the soil physical environment and (iii) modifying the soil biological activities. For example, long term zero tillage produced significantly higher concentrations of P in the surface soil (0-0.05 m), whereas P levels were decreased at the 0.05-0.15 m depth as compared to chisel ploughing [14]. The accumulation of P in the surface soil under zero-tillage was attributed to the lack of physical disturbance that mixes fertilizer P thoroughly within the plough layer [15] and the P immobility in soils. According to Redel *et al.* [16] and Zamuner [17], the accumulated P gradually saturates the high P affinity in the acid soils' surface layer, decreasing the binding energy of P hence increasing its availability [18; 19].

Wortmann [20] observed that lime mobility in soils is about 1.27cm per year on fine textured soils, hence taking several years to reach considerable depths. This makes it difficult to ameliorate subsurface acidity through surface liming alone and makes a combination of deep tillage and incorporation of lime an important method for ameliorating subsurface soil acidity. Deep tillage has also been observed by Bollard and Brennan [21] to aid in mixing previously applied P fertilizer, hence improving the effectiveness of P fertilizer for subsequent crops.

Soil acidity management practices such as use of organic materials as an alternative to liming, liming and breeding for acid tolerant maize germplasms [22; 23; 24; 25; 26] have been widely evaluated in some parts of Kenya. Despite the significant effects of tillage on soil physical, chemical and biological properties, the role of tillage methods in soil acidity management have however received limited attention in Kenya. The study, therefore, aimed at evaluating (i) the effects of tillage methods on selected soil chemical properties and (ii) the interaction effects of tillage methods, lime and phosphorus application in the management of soil acidity in Kenya.

2.0 MATERIALS AND METHODS

2.1 Experimental design, layout and crop husbandry

A field experiment was conducted at Waruhiu Agricultural Training Centre (ATC), Githunguri, Kiambu County, to evaluate the effects of tillage, lime and P applications on selected properties of acid soils. Treatments were laid out in a Randomized Complete Block Design with split plot arrangement and

replicated three times. Main plots consisted of tillage practices while subplots were fertilizer P and lime treatments. Tillage practices evaluated were: ploughing (15 cm), hand-hand hoe tillage (5-10 cm) and double-digging strip tillage (30 cm deep) using modified hand hoe 15 cm wide. Fertilizer and lime treatments were DAP (Diammonium Phosphate) + lime (DAPL), TSP (Triple super phosphate) + lime (LP), TSP alone (P) and lime alone (L). Controls consisted of plots without fertilizer and lime treatments. Plots of 3 m x 4.5 m were planted with certified maize seed, Nduma variety, at the spacing of 75 cm between rows and 30 cm within rows. The distance between blocks was 2 m while 1 m wide spaces separated the subplots. Each subplot consisted of six rows of maize plants with 11 plants in each row. The two outer rows acted as guard rows, while sampling was done in the four inner rows.

Lime at the rate of 3.2 tones ha^{-1} was applied three weeks before planting during land preparation and thoroughly mixed with soils in the lime treatment plots. Other fertilizer treatments were applied during planting, and a blanket amount of calcium ammonium nitrate (CAN) 100 kg N ha^{-1} was applied to all treatments except control and those treated with DAP. Weeding was done using hand hoe but strip tillage plots were weeded by clearing using a panga. Top dressing was carried out when the crop was knee high using CAN at a rate of 100 kg N ha^{-1} . Triple superphosphate (TSP) fertilizer was used as P source. All P applications were done at a rate of 52 kg P ha^{-1} . Data collected included, soil pH, extractable P, CEC, Ca, Mg and exchangeable Al.

2.2 Soil Characterization

Soil physicochemical properties and lime requirement of the soils in the research plots were evaluated before planting and after harvesting. Subsoil samples were taken with a soil auger from the topsoil (0-30 cm) based on procedures described by Carter and Gregorich [27]. The composite samples were then packed in polythene bags, properly labelled and taken to the laboratory for both physio-chemical analyses. Laboratory analyses were carried out as described by Okalebo [28] and soil characterization data in Table 1 was used for lime requirement determinations.

2.3 Data analysis

For each variable determined, data were subjected to Analysis of Variance (ANOVA) using the PROC ANOVA procedure of GenStat (Lawes Agricultural Trust Rothamsted Experimental station 2011, version 14.2) [29]. Means were ranked using the Duncan's New Multiple Range Test.

3.0 RESULTS

3.1 Initial soil chemical and physical characteristics

Some of the chemical and physical properties of the soil used in the study are presented in Table 1. The soil was strongly acidic, with low pH values (4.5-5.0). The exchangeable aluminium and % aluminium saturation was high ($> 2 \text{ cmol kg}^{-1}$ soil and $> 20\%$ Al, respectively). The standard phosphate requirements (SPR) of the soils were also high ($> 150 \text{ mg kg}^{-1}$ soil) while available P and CEC were low ($< 30 \text{ mg kg}^{-1}$ Mehlich P and $< 15 \text{ cmol kg}^{-1}$ soil, respectively).

Table 1: Some baseline physical and chemical properties of the soil at the study site

	Long rains	Short rains
--	------------	-------------

pH (1:2.5 soil:water suspensions)	4.7	4.8
Exch. Al (cmol kg ⁻¹)	2.5	2.6
Total N (%)	0.3	0.3
OC (%)	2.5	2.4
Extractable P (mg kg ⁻¹)	20.0	11.0
Exchangeable K (cmol kg ⁻¹)	0.8	0.8
Exchangeable Ca (cmol kg ⁻¹)	3.5	2.1
Exchangeable mg (cmol kg ⁻¹)	3.2	3.2
Exchangeable Na (cmol kg ⁻¹)	0.2	0.2
CEC	11.9	12.4
AL Saturation (%)	35.1	37.7
SPR mg kg ⁻¹ soil	257.0	260.0
PSD*		
% Clay	9	12
% Silt	31	31
% Sand	60	57
Textural Class	Sandy loam	Sandy loam

*Particle size distribution; SPR** Standard phosphate requirement defined as the amount of P required to raise equilibrium solution P level to 0.2 mg P L⁻¹; Long rains- March to June rains; Short rains- October to December rains.

3.2 Effects of Tillage, Phosphorus and lime application on soil pH

Combination of tillage, phosphorus and lime application significantly ($P \leq 0.05$) increased the acid soils pH values (Figure 1). Combination of plough tillage, lime and P inform of TSP was observed to have the highest ($P \leq 0.05$) soil pH increase in the two seasons compared to other treatments. The mean soil pH increase was > 38% compared to the control.

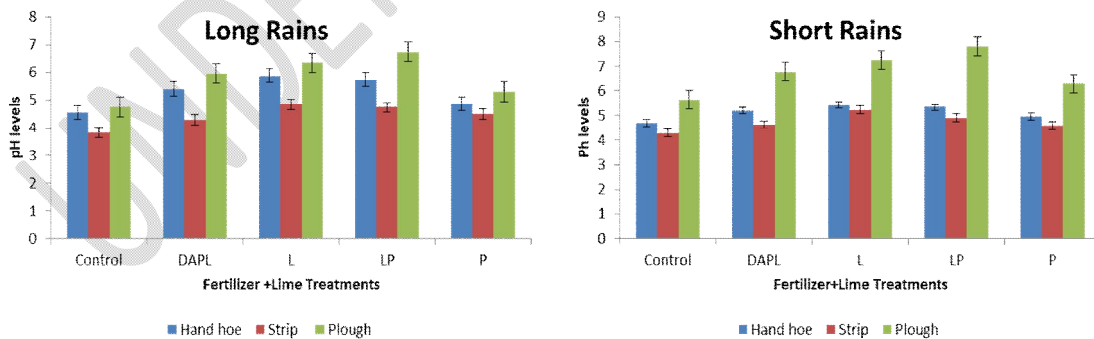


Figure 1: Effect of Tillage-P-lime interaction on pH of acid soils

3.3 Effects of Tillage, Phosphorus and lime application on exchangeable phosphorus

Extractable P was significantly ($P \leq 0.05$) increased by Tillage-P-lime interactions (Table 2). Plough-DAPL interaction was observed to have the highest extractable P levels during the long rains while the P levels from plough-DAPL and plough-LP interactions were not significantly different during the

short rains. Phosphorus levels in Plough DAPL treated soils were 81% higher than control and 49% higher than strip tillage in the long rains. Phosphorus levels in Plough DAPL and Plough LP was 75% higher than control in during the short rains. Tillage methods did not have significant effect on phosphorus levels.

Table 2: Effect of Tillage-P-lime interaction on extractable P (mg kg⁻¹) in acid soils

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	12.80a	12.70a	10.40a	15.00a	9.30a	18.80a
DAPL	46.60b	28.40b	55.60b	44.70b	29.20b	72.80b
L	18.30a	9.30a	17.50a	19.10a	11.40a	22.80a
LP	43.40b	38.10c	37.40c	41.70b	36.00b	74.20b
P	27.00ac	28.40b	28.60ac	27.00c	16.60a	30.80c
% CV	3.90	3.90	3.90	2.90	2.90	2.90

DAPL -DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at $P \leq 0.05$.

3.4 Effects of Tillage, Phosphorus and lime application on cation exchange capacity

Cation exchange capacity (CEC) was significantly increased by Tillage-P-lime interactions (Table 3). Although the plough-LP and plough-DAPL interactions gave the highest CEC values compared to the other treatments during both the long and short rains, CEC values from both plough-DAPL and plough-LP were not significantly ($P \leq 0.05$) different. Plough DAPL increased CEC BY 49% and 35% during long and short rains respectively compared to control while plough LP increased CEC by 52.5% and 68% during long and short rains respectively compared to control. The CEC of control-hand hoe and control-strip tillage were observed to be lower than the initial soil CEC of 11.9 cmols kg⁻¹ as presented in Table 3.

Table 3: Effect of Tillage-P-lime interaction on cation exchange capacity (CEC) (cmol kg⁻¹) in acid soils

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	8.04a	9.75a	16.96a	12.11a	12.59a	12.58a
DAPL	16.57b	12.79c	33.31b	13.58a	15.53b	35.42b
L	12.53c	12.50c	25.97c	10.54a	10.36a	17.42a
LP	15.37b	17.80b	35.85b	15.38ab	15.41b	39.02b
P	13.97c	17.13b	29.77d	11.98a	13.18ab	20.99a
% CV	4.60	4.60	4.60	8.90	8.90	8.90

DAPL -DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at $P \leq 0.05$.

3.5 Effects of Tillage, Phosphorus and lime application on exchangeable calcium

Exchangeable Ca values varied among treatments and seasons (Table 4). During the long rains, strip tillage-LP interaction significantly ($P \leq 0.05$) gave the highest exchangeable Ca levels while plough-LP interaction gave the highest Ca levels during the short rains. Exchangeable Ca in strip LP was 46% higher than control while calcium levels in Plough was 52% higher than control. Sole tillage methods did not however significantly affect Calcium levels during the two seasons.

Table 4: Effect of Tillage-P-lime interaction on exchangeable Ca (cmol kg^{-1}) in acid soils

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	2.86a	2.91a	2.34a	2.00a	2.07a	2.67a
DAPL	4.45b	4.69b	4.19b	3.65b	3.22a	4.64b
L	4.15b	4.47b	3.53b	3.35ab	2.93a	3.55a
LP	5.04c	5.36c	4.86c	4.32c	4.11c	5.47c
P	5.12c	4.86b	3.84b	4.24c	3.49c	4.20b
% CV	1.30	1.30	1.30	2.70	2.70	2.70

DAPL -DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at $P \leq 0.05$.

3.6 Effects of Tillage, Phosphorus and lime application on exchangeable magnesium

Magnesium levels varied greatly among treatments and seasons (figure 2). Plough-LP interaction significantly ($P \leq 0.05$) promoted the highest magnesium levels during both long and short rains. Plough LP increased available Mg by 45% and 62% during long and short rains respectively compared to control. Sole tillage methods did not significantly affect magnesium levels.

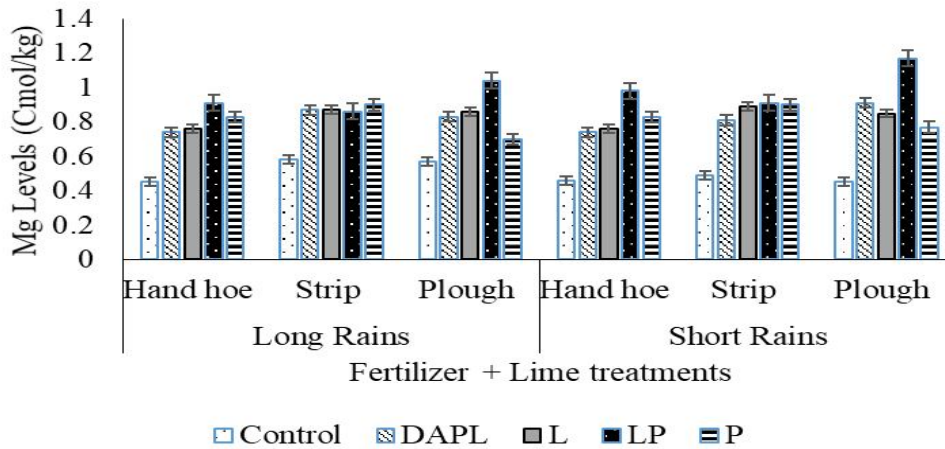


Figure 2: Effect of Tillage-P-lime interaction on exchangeable magnesium (cmol kg^{-1}) in acid soils

3.7 Effects of Tillage, Phosphorus and lime application on exchangeable Aluminium

Exchangeable Al in the soils continuously decreased with Tillage-P-lime interactions (Table 5). Ploughing and application of lime and P in form of TSP significant ($P \leq 0.05$) reduced exchangeable aluminium resulting to the lowest Al levels during both the long and short rains. Plough LP led reduced Exchangeable AL by 85.3% and 83.3% during short and long rains respectively compared to

control. DAPL was observed to significantly promote higher levels of exchangeable Al Compared to control and LP in both seasons.

Table 5: Effect of Tillage-P-lime interaction on exchangeable Al (cmol kg⁻¹) in acid soils

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	2.98a	3.32a	2.08a	3.32a	2.14a	2.04a
DAPL	1.68b	2.44b	1.33b	1.56b	1.71b	1.45b
L	1.46b	1.69bc	1.29b	1.34bc	0.98c	0.86c
LP	0.46c	1.01d	0.39c	0.97c	0.57d	0.30d
P	1.37d	2.02b	1.18a	2.64d	1.96a	1.98a
% CV	3.90	3.90	3.90	3.80	3.80	3.80

DAPL -DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at $P \leq 0.05$

4.0 DISCUSSION

The high levels of exchangeable Al (> 2.0 cmol Al kg⁻¹) and Al saturation (> 20%) observed in the present studies are classified by [31] as unsuitable for most maize germplasms grown by farmers in Kenya. Based on the rating set by [7; 30], the available phosphorus in the plough layer of the soils was low and inadequate for supporting optimum crop yields. Additionally, the soil CEC values (< 15 cmol kg⁻¹) and exchangeable Ca²⁺ (< 4.0 cmol kg⁻¹) were limiting [7], implying that the ability of the soil to avail most plant nutrients from the exchange complex for plant uptake was low.

The significant increase of soil pH, CEC and Ca upon ploughing, liming and application of P fertilizers could be attributed to the thorough mixing of soils with lime and P fertilizers through the ploughing process. This might have resulted in the manipulation of the physical, chemical and biological processes in the soils [32] leading to displacement of Al³⁺, H⁺, and Fe³⁺ ions by Ca²⁺ ions from the lime (CaO) and TSP fertilizer. When liming material (CaO) is added to the acid soils, it reacts with carbon dioxide and water to yield Ca bicarbonate which reacts with the exchangeable and residual acidity with consequent replacement of the H⁺ and Al³⁺ on the colloidal complex by Ca²⁺ [33; 34]. The adsorption of the calcium ions lowers the percentage acid saturation of the colloidal complex and the pH of the soil solution increases hence increased adsorption of bases on the exchange complex [35; 36]. Similar results have been reported by [37; 38; 39; 40].

The lower pH values in soils treated with DAPL as compared to LP could be attributed to the H⁺ produced during biological oxidation of ammonium (nitrification) into nitrates for plant uptake. Similar observations and trends were reported by [41; 42]. Mwangi [42] observed that the topsoil pH of soils supplied with 23:23:0/CAN or DAP / CAN gradually decreased over the years while the pH of soils where TSP/CAN were applied remained constant. Similarly, Manoharan [41], working on pastures in New Zealand, observed that soil acidification was more pronounced in DAP treated plots, and this led

to significantly low soil pH, exchangeable Ca, and Ca saturation, and increased soluble Al and exchangeable acidity.

Increased soil extractable P on Plough-DAPL and Plough-LP interactions as compared to other interactions can be attributed to stimulation of soil organic P mineralization by tillage and lime [43]. Ploughing the soils might have disrupted soil aggregates resulting in concomitant organic matter oxidation; increased aeration and porosity hence increased the microbial activities and net mineralization of P from soil organic P [44; 45; 15]. Comparing effects of P alone and lime alone, the significant increase of soil available P after application of P alone as compared to lime alone could be attributed to the provision of starter P to the soils which have very low soil solution P. Antoniadis [45] reported similar findings in a greenhouse experiment and concluded that P alone was more beneficial than lime alone when soils had low initial P levels while lime alone was beneficial when the soils had moderate initial P levels.

The significant increase of soil pH, extractable P, Ca, CEC, and reduction of exchangeable Al by plough tillage compared to other tillage methods can be attributed to enhanced rate of soil reactions due to improved soil porosity resulting from deep turning and mixing of the soil, lime and P fertilizer ([45]. Similar findings have been reported by [46; 47]

5.0 CONCLUSIONS

Interaction between lime, phosphorus and tillage methods significantly increased soil pH, extractable P, exchangeable Ca, CEC, and reduced exchangeable Al. Combining plough tillage with Phosphorus in form of TSP and lime application was observed to significantly increase soil pH, P, CEC, Ca and Mg, and reduced exchangeable Al while combination of plough tillage, phosphorus in form of DAP and lime application was observed to significantly increase extractable P, CEC and AL. Combination of strip tillage, lime and Phosphorus in form of TSP on the other hand, increased exchangeable Ca in the soils. It can be concluded that integrating ploughing with either LP or DAPL can be possible options in the management of soil pH, available P, calcium, magnesium, Aluminium and CEC in acidic soils. Further studies are, however, required to ascertain the long-term effects of the tillage methods on such soils for sustainable soil health and productivity.

6.0 REFERENCES

1. Kanyanjua SM, Ileri L, Wambua S, Nandwa SM. Acid soils in Kenya: Constraints and remedial options. KARI Technical Note. 11:24.
2. Obura PA. *Effects of soil properties on bioavailability of aluminium and phosphorus in selected Kenyan and Brazilian soils*. PhD Thesis, Purdue University, USA. 2008; pp. 1-57.

3. Sombroek WG, Braun HMM, van de Pouw. Exploratory soil map and agro-climatic zone map of Kenya. Scale 1:1000, 000. Exploratory Soil Survey Report No. E1. Kenya Soil Survey, Nairobi. 1982; pp. 1-78.
4. Otinga AN. Madini Adimu, Chakula Tosha. Coping with phosphorus limitations: Allocation of phosphorus in maize based cropping systems in Western Kenya. Dissertation for the award of PhD at Katholieke Universiteit, Leuven, Belgium. 2012; pp. 1-63.
5. Muindi, EM, Semu E, Mrema JP, Mtakwa PW, Gachene CK, Njogu MK. Soil Acidity Management by Farmers in the Kenya Highlands. *Journal of Agriculture and Ecology Research International*, 2016; 5(3): 1-11.
6. Kisinyo PO. Constraints of soil acidity and nutrient depletion on maize (*Zea mays* L.) production in Kenya. PhD thesis, Moi University, Kenya. 2011
7. Landon JR. *Booker Tropical Soils Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*. New York: John Wiley and Sons. 1991
8. Ligeyo, D.O. Genetic analysis of maize (*Zea Mays* L.) tolerance to aluminium toxicity and low phosphorus stress and development of synthetics for use in acid soils of western Kenya. PhD. Thesis. Moi University, Eldoret, Kenya. 2007; pp. 1-71.
9. Muindi, EM, Mrema JP, Semu E, Mtakwa PW, Gachene CK, Njogu MK. Phosphorus adsorption and its relation with soil properties in acid soils of Western Kenya. *International Journal of Plant and Soil Science*, 2015; 4(3):203-211.
10. Muindi EM, Mrema JP, Semu E, Mtakwa PW, Gachene C.K. Phosphate sorption characteristics and external phosphorus requirements of Nitisols in Central Kenya Highlands. *International Journal of Soil Science*, 2017; 12(3):113-119.
11. Muindi EM. Understanding Soil Phosphorus. A Review. *International Journal of Soil Science*, 2019; 31(2):1–18.
12. Tiecher T, Santos DR, Kaminski J, Calegari A. Forms of inorganic phosphorus in soil under different long term soil tillage systems and winter crops. *Brazilian Journal of Soil Science*, 2012; 36:271-281
13. Robson AD, Taylor AC. The effect of tillage on chemical fertility of soil. In: *Tillage: New directions in agriculture*. Inkata Press, Melbourne. 1987; pp. 284- 307.
14. Andraski TW, Bundy L.G, Kilian KC. Manure history and long-term tillage effects on soil properties and phosphorus losses in runoff. *Journal of Environmental Quality*, 2003; 32:1782-1789.
15. Selles F, Kochhann RA, Denardin JE, Zentner RP, Faganello A. Distribution of phosphorus fractions in a Brazilian Oxisol under different tillage systems. *Soil and Tillage Research*, 1997; 44: 23-34.
16. Redel YD, Rubio R, Rouanet JL, Borie F. Phosphorus bioavailability affected by tillage and crop rotation on a Chilean volcanic derived Ultisol. *Geoderma*, 2007; 139:388-396.
17. Zamuner EC, Picone LI, Echeverria HE. Organic and inorganic phosphorus in mollisol under different tillage practices. *Soil and Tillage Research*, 2008;99: 131-138.
18. Rheinheimer DS, Anghinoni I. Distribution of inorganic phosphorus in soil management systems. *Brazil Agricultural Research*, 2001; 36: 151-160.

19. Rheinheimer DS, Anghinoni I, Conte E. Phosphorus sorption in soil in relation to the initial content and soil management. *Journal of Soil Science*, 2003; 27 (1):41-49.
20. Wortmann C, Mamo M, Shapiro C. *Management Strategies to Reduce the Rate of Soil Acidification*. University of Nebraska, Lincoln. 2003; 1503pp.
21. Bollard MDA, Brennan RF. Phosphorus, copper and zinc requirements of no-till wheat crops and methods of collecting soil samples for soil testing. *Australian Journal of Experimental Agriculture*, 2006; 46:1051-1059.
22. Opala PA, Okalebo EJ, Othieno EC, Kisinyo EP. Effect of organic and inorganic phosphorus sources on maize yields in an acid soil in Western Kenya. *Nutrient Cycling in Agroecosystems*, 2010; 86:317-329
23. Opala PA, Nyambati RO, Kisinyo PO. Response of maize to organic and inorganic sources of nutrients in acid soils of Kericho County, Kenya. *American Journal of Experimental Agriculture*, 2014; 4(6):713-723.
24. Ouma E, Ligeyo D, Matonyei T, Agalo J, Were Be, Too E, Onkware, Gudu S, Kisinyo P, Nyangweso P. Enhancing maize grain yield in acid soils of Western Kenya using aluminium tolerant germplasm. *Journal of Agricultural Science and Technology*, 2013; 3:33-46
25. Rewe MK, Muindi E, Ndiso J, Kinusu K, Mailu S, Njeru P, Rewe T. Effect of Bioslurry from Fixed Dome and Tubular (Flexi) Biodigesters on Selected Soil Chemical Properties, Maize (*Zea mays*) Growth, Yield and Quality. *International Journal of Plant & Soil Science*, 2021; 33(20): 158-171.
26. Rewe MK, Muindi E, Ndiso J, Kinusu K, Mailu S, Njeru P, Rewe T. Integrated effect of liquid bioslurry and inorganic fertilizer on selected soil chemical properties, maize (*Zea mays*) growth, yield and grain quality. *African Journal of Crop Sciences*, 2022;10(5): 1-16.
27. Carter MR, Gregorich EG. *Soil sampling methods for analysis*, 2nd Ed; Taylor and Francis, Boca Raton. 2007; 1264pp.
28. Okalebo, J., Robert, W., Gathua, K., & Woome P. L. (Laboratory Methods of Soil and Plant Analysis: A Working Manual 2nd ed. Sacred Africa.2002.
29. GenStat (2010). The GenStat Teaching Edition. GenStat Release 7.22 TE, Copyright 2008, VSN International Ltd. 2010.
30. Mehlich AA, Pinkerton RW, Kempton R. Mass analysis methods for soil fertility evaluation. Internal Publication, Ministry of Agriculture, Nairobi. 1962; pp. 1-21.
31. Landon JR. *Booker Tropical Soils Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*. New York: John Wiley and Sons.1991
32. Guan GM, Zhang JE, Yan HC, Xu RB. Review on influences of no tillage on soil fertility of paddy field. *China Agricultural Science Bulletin*, 2005; 21(278):266-269
33. Weil R, Brady NC. The nature and properties of soil. 15th edition. Pearson. 2017:1104.
34. Muindi EM. Effects of liming on dithionate and oxalate extractable aluminium in acid soils. *Asian Journal of Soil Science and Plant Nutrition*, 2020; 5(3):1-9
35. Nelson PN, Su N. Soil pH buffering capacity: a descriptive function and its application to some acidic tropical soils. *Australian Journal of Soil Research*, 2010; 48: 210-217.

36. Martins AP, Anghinoni I, Costa SEVGA, Carlos FS, Nichel GH, Silva RAP, Carvalho PCF. Amelioration of soil acidity and soybean yield after surface lime reapplication to a long-term no-till integrated crop-livestock system under varying grazing intensities. *Soil and Tillage Research*,2014; 144: 141-149.
37. Kamprath EJ. Crop response to lime in the tropics, In: *Soil acidity and liming*. 2nd Ed; (Edited by Adams F.) Agronomy and Soil Science Society of America, Madison. 1984; pp. 349-368.
38. The C, Calba H, Zonkeng C, Ngonkeu ELM, Adetimirin VO. Response of maize grain yield to changes in acid soil characteristics after soil amendment. *Plant and Soil*, 2006; 284:45-57.
39. Fageria NK, Baligar VC, Zobel RW. Yield, nutrient uptake and soil chemical properties as influenced by liming and boron application in common bean in a no-tillage system. *Communications in Soil Science and Plant Analysis*,2007; 38 (11-12): 1637-1653.
40. Auxtero E, Madeira M, Parker D. Extractable Al and soil solution ionic concentrations in strong leached soils from Northwest Iberia: Effects of liming. *International Scholarly Research Network*, 2012; 1: 15.
41. Manoharan V, Loganathan P, Tillman RW. Effects of long term application of phosphate fertilizers on soil acidity under pasture in New Zealand. In: *Plant and soil interactions at low pH*. Springer, Netherlands. 1995; pp. 85-91.
42. Mwangi TJ, Ngeny JM, Wekesa F, Mulati J. Acidic soil amendment for maize production in Uasin Gishu District, North Rift Kenya. In: *Proceeding of 2nd scientific conference of soil management and legume research network project: Participatory technology development by small holders in Kenya*. (Edited by Gachene *et al.*) Nairobi, Kenya, 2002; pp 37 - 46.
43. Haynes RJ. Effects of liming on phosphate availability in acid soils. *Plant and Soil*, 1982; 68(3):289-308.
44. Buresh RJ, Smithson PC, Hellums DT. Building soil phosphorus capital in Africa. In: *Replenishing soil fertility in Africa*. (Edited by Buresh, P. J. *et al.*) Soil Science Society of America, Madison. 1997; pp. 111-149.
45. Antoniadis V, Hatzis F, Bachsevanidis D, Koutroubas SD. Phosphorus availability in low P and acidic soils as affected by liming and P addition. *Communications in Soil Science and Plant Analysis*, 2015; 46(1):1522-2416.
46. Guan, D, Al-Kaisi MM, Zhang Y, Duan L, Tan W, Mingcai Z, Li Z. Tillage practices affect biomass and grain yield through regulating root growth, root-bleeding sap and nutrients uptake in summer maize. *Field Crops Research* 2014; 157:89-97.
47. Zhang JJ, Wang Y, Fan TL, Guo TW, Zhao G, Dang Y, Wang L, Li SZ. Effects of different tillage and fertilization modes on the soil physical and chemical properties and crop yield under winter wheat / spring corn rotation on dry land of east Gansu, Northern China. *Ying Yong Sheng Tai Xue Bao*, 2023; 24(4):1001-1008.