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Comparative analysis of immediate and residual effects of farmyard manure, triple superphosphate, and lime on maize yields in western Kenya

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The effects of farmyard manure (FYM) and triple superphosphate (TSP) as sources of phosphorus, when applied with or without lime, on selected soil chemical properties, and the initial and residual maize yields, were compared for two consecutive seasons at two acidic, phosphorus-deficient sites, Khwisero and Maseno, in western Kenya. Nutrient inputs, consisting of two sources of phosphorus: TSP and FYM, applied as sole or in combination at two rates of 30 and 60 kg P ha^{-1}, and lime were applied in the first season only. All treatments with lime maintained the soil pH above 5.5 and reduced exchangeable acidity for the two seasons. Application of FYM also raised the soil pH, but this did not exceed 5.5, and also significantly reduced exchangeable acidity, especially at Khwisero. Sole application of TSP failed to significantly increase maize yields above the control with no nutrient inputs likely due to aluminium toxicity. Sole application of FYM, however, significantly increased maize yields above the control with no nutrient inputs due to the nutrients it contained and its ability to reduce Al toxicity. When TSP was combined with lime or FYM, the deleterious effects of soil acidity were ameliorated and maize responded to the applied TSP. Application of FYM to provide 60 kg P ha^{-1} together with lime gave the highest maize grain yields at both sites in both seasons. FYM treatments had the highest residual maize yields but inorganic fertilizers did not show significant residual effects. Combining lime with FYM at 60 kg P ha^{-1} is a promising strategy to manage acidity and P deficiency at these sites.

Key words: Farmyard manure, lime, phosphorus, soil acidity, residual effects, western Kenya.

INTRODUCTION

Acid soils are prevalent in western Kenya and cover 17 to 24% of the cultivated area under maize, which is the staple food crop in the region (Hijbeek et al., 2021). Coincidentally, these are also the high rainfall areas, which under appropriate management, have the potential to contribute significantly to food security in Kenya. For several decades, maize has successfully been grown in these soils but overuse of acidifying fertilizers, particularly diammonium phosphate and urea, has exacerbated their acidity. There is now irrefutable evidence that yields of maize are declining in the region due to the increasing soil acidification (Muraya and Ruigu, 2017; Kanyanjua et

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al., 2002) posing a serious threat to food security for millions of residents who rely on subsistence farming.

Acid soil infertility is a complex interaction of several growth-limiting factors (Rengel, 2003). It reduces crop growth by causing deficiencies of major nutrients and inducing the toxicity of aluminium (Al), manganese (Mn), iron (Fe) and hydrogen (H) ions which adversely affect plant physiological processes (Marschner, 2012; Foy, 1984). Soil acidity also aggravates P deficiencies by enhancing the fixation of the applied phosphate fertilizers. Furthermore, crops do not respond to nutrient inputs in acidic soils unless soil acidity is ameliorated (Opala et al., 2018). Strategies to manage soil acidity must therefore be undertaken concurrently with those targeted at improving the soil P status. Liming is the most common and one of the most effective ameliorative strategies for improving crop production in acid soils (Hayes, 2018; Fageria and Baligar, 2008), but its use in western Kenya has encountered challenges because of various factors. In particular, large quantities of lime are required for application per unit area in order to correct acidity to levels necessary for maize growth. However, most subsistence farmers have limited financial resources to purchase the required quantities. In addition, fertilizer inputs must be applied with lime for effective crop production and this increases the total cost of production. Organic materials (OMs) have been proposed as alternatives to lime because they can provide plant nutrients while concomitantly correcting acidity and therefore reducing the cost of production (Wong et al., 1998). However, the inadequate quantities available on most smallholder farms remain a major constraint to the utilization of OMs (Stewart et al., 2020). Furthermore, the vast majority of the OMs used by smallholder farmers are of poor quality (Palm et al., 2001) and therefore cannot effectively mimic the effects of lime. Alternative approaches in the management of soil acidity therefore continue to be explored. One aspect that has received little attention is the combination of lime with organic inputs such as farmyard manure (FYM). It is hypothesized that lime can partly provide the immediate effect of increasing soil pH and reducing exchangeable acidity, therefore eliminating Al toxicity, while the OMs provide the requisite nutrients for immediate and residual responses to the crop at a cheaper cost than inorganic fertilizers. The objective of this study was, therefore, to compare the effects of farmyard manure (FYM) and triple superphosphate (TSP) as sources of P, when applied with or without lime, on selected soil chemical properties, and the initial and residual maize yields in western Kenya.

MATERIALS AND METHODS

The study area

Two sites, Khwisero and Maseno, with contrasting agroecological conditions, in western Kenya were used. Khwisero is at 1430 m above sea level on 0.28° N latitude and 34.75° E longitude while Maseno is at 1529 m above sea level on latitude 0.06° S and longitude 34.5° E. The mean annual rainfall at Khwisero and Maseno is 1280 and 1510 mm, respectively. The rainfall pattern at both sites is bimodal with a ‘long rains’ season between March and July and a ‘short rains’ season between September and December. The initial soil properties at the sites are presented in Table 1. The soils at both sites are very acidic (pH < 5.0). The organic C content at Maseno is above the optimum level of 2% while Khwisero has low organic C. The soil at Khwisero is classified as an acrisol while that at Maseno is a ferralsol. The exchangeable acidity and Al levels were higher at Khwisero than at Maseno. Both sites are low in most macro and micronutrients, hence infertile.

Experimental layout and management

The study used randomized complete block design with 12 treatments (Table 2) replicated three times. Lime was applied at 4 t ha^{-1} based on previous studies in the region (Opala et al., 2018; Kisinyo et al., 2014). The lime had the following characteristics: pH of 10, 25% Ca, 4% Mg, and neutralizing value of 70%. The quantity of FYM that was used was calculated after analyzing its nutrient content (Table 3). The manure was of good quality with all its determined parameters being above the optimum requirements.

The study was conducted for two consecutive seasons in the ‘long rains’ (first season) and ‘short rains’ (second season) of 2020. The land was tilled and then harrowed once before the onset of rains in each season. Lime was applied to the appropriate plots by uniformly broadcasting and incorporating it into the top soil four weeks prior to planting during the first season only. This was to allow it ample time to react with the soil to bring about the desired pH rise before planting. Similarly, FYM and TSP (46% P_2O_5) were broadcasted and then incorporated uniformly within the respective plots at the time of planting in the first season only. Treatments with no FYM application received N from calcium ammonium nitrate (CAN) (26% N) at 100 kg ha^{-1} in two splits, 30 kg ha^{-1} at planting and the remaining 6 weeks after planting (WAP). Hybrid maize, H516 variety, was planted and managed using the recommended agronomic practices. In the second season, maize was planted without any nutrient inputs in order to determine the residual effects of the inputs applied in the first season. Each maize crop was harvested at physiological maturity and the grain yield determined at 13.5% moisture content.

Analysis of farmyard manure and soils

The FYM was obtained from a smallholder dairy farmer in Maseno. It was air-dried, sieved and analyzed for nutrients and pH. Soil samples for initial soil characterization were collected from both sites using a soil auger up to a depth of 15 cm before land preparation for the first season crop. These samples were analyzed to determine selected soil chemical and physical properties using standard procedures (Okalebo et al., 2002). Soils were thereafter sampled after every three weeks, for determination of pH, until the maize crop attained physiological maturity of the first season. However, in the second season, pH was determined only twice, prior to planting and at harvesting at both sites. Exchangeable acidity and available P were determined on soils sampled at planting and at 9 WAP of the first season and prior to planting (21 WAP of first season crop) and at harvesting of the second season (42 WAP of first season crop) at both sites. Soil pH was determined using a glass electrode pH meter in a soil:water ratio of 1:2.5 (Rhoades, 1982). Exchangeable acidity was extracted using unbuffered 1 M KCl followed by titration with NaOH (Anderson and Ingram, 1993). Available soil phosphorus was determined by the

Table 1. Initial soil properties of the sites Maseno and Khwisero.

Soil property	Maseno	Khwisero
pH (1:2.5 Soil:H_2O)	4.93	4.65
Total Organic Carbon (%)	2.21	1.41
Total Nitrogen (%)	0.18	0.16
Available P (ppm)	7.41	4.57
Calcium (ppm)	446	105
Magnesium (ppm)	101	22.3
Potassium (ppm)	92.7	46.8
Sulphur (ppm)	15.6	29.9
Zinc (ppm)	5.75	0.92
Copper (ppm)	4.27	2.89
Iron (ppm)	95.2	89.5
Manganese (ppm)	337	89.6
Boron(ppm)	0.08	0.06
CEC	7.32	2.18
Exchangeable acidity (Cmol kg^{-1})	0.93	1.25
Sand (%)	22.8	35.6
Silt (%)	23.4	17.6
Clay (%)	53.7	46.9

Table 2. The experimental treatments.

Treatment	P rate (kg ha^{-1})		
	P from FYM	P from TSP	Total P
Control	0	0	0
0 P + L	0	0	0
TSP (30 P kg ha^{-1})	0	30	30
TSP (30 P kg ha^{-1}) + L	0	30	30
FYM (30 P kg ha^{-1})	30	0	30
FYM (30 P kg ha^{-1}) + L	30	0	30
TSP (60 P kg ha^{-1})	0	60	60
TSP (60 P kg ha^{-1}) + L	0	60	60
FYM (60 P kg ha^{-1})	60	0	60
FYM (60 P kg ha^{-1}) + L	60	0	60
TSP (30 P) + FYM (30 P)	30	30	60
TSP (30 P) + FYM (30 P) + L	30	30	60

P = Phosphorus, FYM = farmyard manure, TSP = triple superphosphate, L=lime.

Olsen method (Olsen et al., 1954) which involved shaking the soil with a 0.5 M $NaHCO_3$ solution and colorimetric determination of the extracted P in a UV spectrotophemeter at 880 nm.

Data analysis

The effects of season, treatment, and their interactions on crop yield were tested using repeated measures ANOVA (General linear model). In addition, all data on available soil P, exchangeable acidity, and maize yield were subjected to ANOVA and treatment means separated by LSD at $p < 0.05$. Quantitative relationships between selected soil parameters (exchangeable acidity and available P) and maize yields were determined by correlation and regression analyses. All data were analyzed using the Genstat statistical package (VSN International, 2022).

RESULTS

Soil pH

The trends in pH during the experimental period are as shown in Figures 1 and 2 for Khwisero and Maseno, respectively. All the treatments with lime applied as sole

Table 3. Characteristics of the farmyard manure used in the study.

pH	C %	N %	P %	K %	Ca %	Mg %	S %	Mn ppm	Fe ppm	Zn ppm	Cu ppm
8.3	28.6	1.74	0.41	1.07	2.05	0.54	0.28	1410	17800	224	47.0

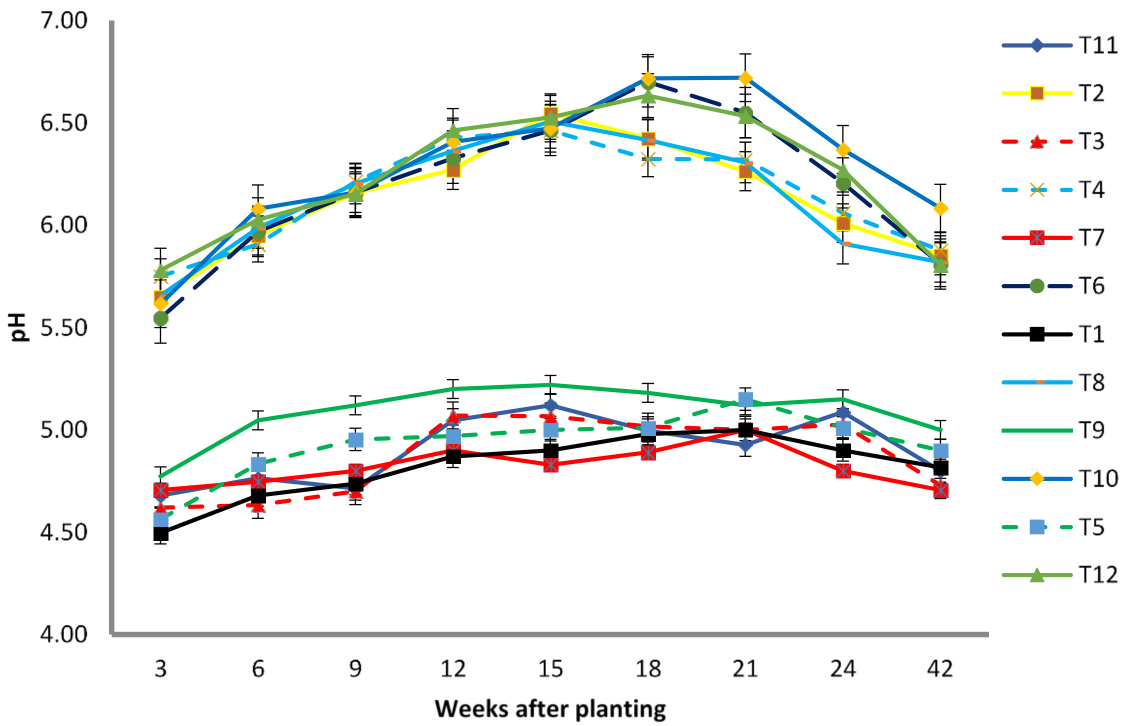

Figure 1. pH trends at Khwisero. T1. No input (Control), T2. Lime (L), T3. TSP (30 P kg ha^{-1}), T4. TSP (30 P kg ha^{-1}) + L, T5. FYM (30 P kg ha^{-1}), T 6. FYM (30 P kg ha^{-1}) + L, T7. TSP (60 P kg ha^{-1}), T 8. TSP (60 kg P ha^{-1}) + Lime, T9. FYM (60 P kg ha^{-1}), T10. FYM (60 P kg ha^{-1}) + L, T11 TSP (30 P)+ FYM (30 P), T 12. TSP (30 P) + FYM (30 P) + L.

or in combination with FYM or TSP significantly increased pH above the control treatment and maintained the pH above 5.5, which is considered the critical level below which there is aluminium toxicity, at all sampling times at both sites. Sole application of FYM at both rates of 30 and 60 kg P ha^{-1} significantly increased the pH above the control but did not raise it above 5.5 at all times at both sites. FYM manure at 60 kg P ha^{-1} gave generally higher pH than 30 kg P ha^{-1} at Khwisero but not Maseno where it was superior up to only 12 WAP. Combining lime with FYM gave significantly higher pH than all other treatments at Maseno from 9 WAP and at Khwisero from 21 WAP to the end of the study.

Exchangeable acidity

The results for exchangeable acidity are shown in Table 4. All treatments with lime (applied either alone or with TSP or with FYM) significantly reduced the exchangeable acidity relative to the control treatment but TSP when applied alone at both P rates of 30 and 60 kg ha^{-1} had no significant effect on exchangeable acidity at both sites. Farmyard manure when applied at 30 or 60 kg P ha^{-1} significantly reduced the exchangeable acidity at all sampling times at Khwisero. At Maseno, however, the reduction was only significant at 21 WAP for FYM applied at 30 kg P ha^{-1} and at 9 and 12 WAP for FYM applied at 60 kg P ha^{-1}. There were no significant differences in exchangeable acidity between the treatments with FYM applied at 30 and 60 kg P ha^{-1} at 9 and 42 WAP at Khwisero. However, FYM applied at 60 P ha^{-1} gave significantly lower levels of exchangeable acidity than FYM applied at 30 kg P ha^{-1} at 21 WAP at this site. At Maseno, the differences in exchangeable acidity as affected by the two rates of FYM were not significant at all times. The addition of lime to FYM, at both P rates, did not significantly alter the exchangeable acidity compared

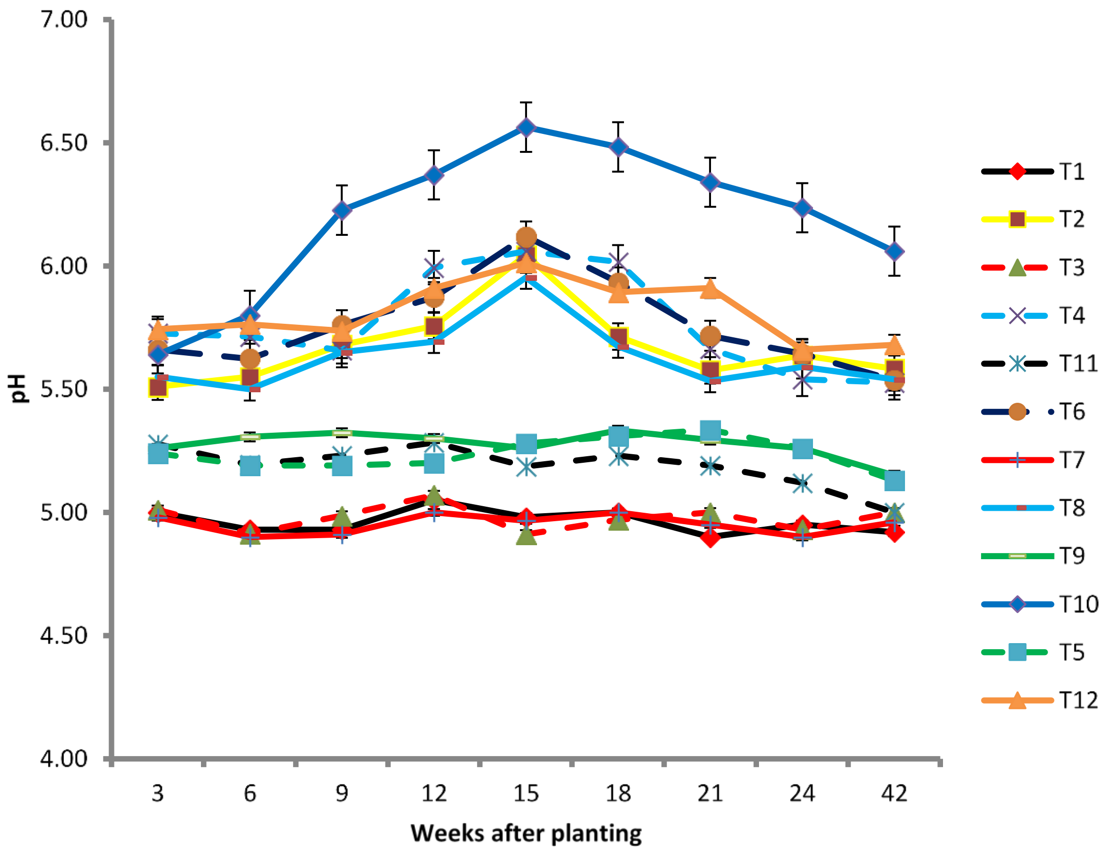

Figure 2. pH trends at Maseno. T1. No input (Control), T2. Lime (L), T3. TSP (30 P kg ha^{-1}), T4. TSP (30 P kg ha^{-1}) + L, T5. FYM (30 P kg ha^{-1}), T 6. FYM (30 P kg ha^{-1}) + L, T7. TSP (60 P kg ha^{-1}), T 8. TSP (60 kg P ha^{-1}) + Lime, T9. FYM (60 P kg ha^{-1}), T10. FYM (60 P kg ha^{-1}) + L, T11 TSP (30 P) + FYM (30 P), T 12. TSP (30 P) + FYM (30 P) + L.

Table 4. Effect of lime, farmyard manure and inorganic phosphate on exchangeable acidity.

Treatment	Sampling time (Weeks after planting)					
	Khwisero			Maseno		
	9	21	42	9	21	42
1. Control	1.16	1.22	1.22	0.90	0.97	0.90
2. 0 P + L	0.08	0.09	0.07	0.12	0.12	0.08
3. TSP (30 P kg ha^{-1})	1.23	1.20	1.09	0.79	0.90	0.92
4. TSP (30 P kg ha^{-1}) + L	0.09	0.17	0.07	0.16	0.11	0.08
5. FYM (30 P kg ha^{-1})	0.86	1.03	0.82	0.84	0.79	0.80
6. FYM (30 P kg ha^{-1}) + L	0.07	0.09	0.09	0.11	0.11	0.10
7. TSP (60 P kg ha^{-1})	1.13	1.23	1.06	0.84	0.87	0.88
8. TSP (60 P kg ha^{-1}) + L	0.06	0.08	0.07	0.08	0.10	0.11
9. FYM (60 P kg ha^{-1})	0.81	0.88	0.81	0.76	0.83	0.82
10. FYM (60 P kg ha^{-1}) + L	0.07	0.93	0.07	0.08	0.08	0.09
11. TSP (30 P) + FYM (30 P)	0.83	1.01	0.93	0.85	0.74	0.71
12. TSP (30 P) + FYM (30 P) + L	0.06	0.11	0.29	0.13	0.13	0.11
LSD	0.12	0.11	0.13	0.16	0.14	0.15
CV %	13.5	11	14.6	19.5	17.1	19.2

TSP=Triple superphosphate, FYM= farmyard manure, P = phosphorus, LSD= least significant difference, CV= coefficient of variation, WAP= weeks after planting, LAST= the end of the second season. Lime was applied at a rate of 8 t ha^{-1} at planting of the first season only.

Table 5. Effect of lime, farmyard manure and inorganic P on available P.

Treatment	Sampling time (weeks after planting)					
	Khwisero			Maseno		
	9	21	42	9	21	42
1. Control	4.12	4.46	3.84	6.50	7.59	6.11
2. 0 P + L	5.42	4.91	4.20	8.66	8.81	8.64
3. TSP (30 P kg ha^{-1})	5.76	6.20	4.86	9.08	8.55	7.46
4. TSP (30 P kg ha^{-1})+ L	7.02	5.31	5.95	8.92	9.01	9.02
5. FYM (30 P kg ha^{-1})	5.29	5.34	5.66	7.32	9.29	8.32
6. FYM (30 P kg ha^{-1}) + L	5.54	6.11	5.22	8.27	8.80	7.61
7. TSP (60 P kg ha^{-1})	10.07	7.09	5.83	9.82	11.72	8.98
8. TSP (60 P kg ha^{-1})+ L	10.26	6.85	5.53	11.60	12.85	9.04
9. FYM (60 P kg ha^{-1})	5.86	7.27	6.90	8.88	10.13	7.67
10. FYM (60 P kg ha^{-1}) + L	8.69	7.54	7.49	10.76	11.32	10.70
11. TSP (30 P)+ FYM (30 P)	10.71	8.09	6.56	12.55	10.01	9.36
12. TSP (30 P)+ FYM (30 P)+ L	8.18	7.85	6.66	10.58	11.19	9.75
LSD	1.60	1.96	2.28	2.35	2.12	3.48
CV%	17.1	17.8	21.5	18.8	12.3	23.5

TSP=Triple superphosphate, FYM= farmyard manure, P = phosphorus, LSD= least significant difference, CV= coefficient of variation. Lime was applied at a rate of 8 t ha^{-1} at planting of the first season only.

to the application of lime alone at all times. Similarly, the treatments with FYM combined with lime had similar exchangeable acidity levels with those of TSP applied with lime at equivalent P rates.

Available soil phosphorus

Application of sole lime did not significantly increase the available soil P above the control, with no P input at both sites at all sampling times (Table 5). At 9 WAP, all P inputs irrespective of source significantly increased available P at both sites except FYM applied as sole or with lime at 30 kg P ha^{-1} at both sites and FYM applied at 60 kg P ha^{-1} at Khwisero (Table 5). At 21 WAP, however, only treatments with P applied at 60 P ha^{-1} gave significantly higher levels of available soil P than the control at both sites. By the 42nd WAP, only treatments with FYM applied as sole or with lime at 60 P ha^{-1} had significantly higher available P than the control at Khwisero. At Maseno, only FYM applied with lime, or FYM applied with TSP and lime, at 60 kg P ha^{-1} increased the available soil P above the control at 42 WAP. At similar P rates, treatments with soil application of FYM and TSP are not significantly different in available soil P at this time. Application of lime with TSP or FYM did not confer any advantage in terms of increasing available P for comparable P rates of FYM or TSP applied without lime at both sites at all times.

Maize yield

The maize yield data are presented in Table 6. At Khwisero, the yields ranged from 0.53 (TSP (30 P kg ha^{-1}) to 4.49 t ha^{-1} (FYM (60 P kg ha^{-1}) + L)) in the first season and 0 (sole TSP at 30 and 60 P kg ha^{-1}) to 3.13 t ha^{-1} (FYM (60 P kg ha^{-1}) + L) in the second season. The yields at Maseno, ranged from 0.55 (control) to 4.26 t ha^{-1} (FYM (60 P kg ha^{-1}) + L) in the first season and 0.55 (control) to 3.32 t ha^{-1} (FYM (60 P kg ha^{-1}) + L) in the second season. The effect of the season was highly significant ($p < 0.001$) with the mean yields of the first being higher than the second season. Site effects were only significant in the second season when Maseno recorded higher yields than Khwisero. The interaction between treatment and site or treatment by season was also significant.

Application of lime without P inputs did not significantly increase yields at Maseno in both seasons and at Khwisero in the first season. However, lime alone significantly increased maize yields above the control at Khwisero in the second season. Triple superphosphate when applied without lime at both 30 and 60 kg P ha^{-1} did not significantly increase yields above the control at both sites in both seasons. When applied with lime, TSP at both rates (30 and 60 kg P ha^{-1}) significantly increased yields above the control at Khwisero in both seasons but only in the first season at Maseno.

The combination of lime with FYM at P rate of 30 kg ha^{-1} gave yields that were not significantly different from those of lime and TSP at the same P rate at both sites in the first season.

However, in the second season, FYM applied with lime at 30 kg P ha^{-1} was significantly better than TSP (30 kg P ha^{-1}) with lime but the opposite was true at Khwisero. Combining a higher rate of FYM (60 P ha^{-1}) with lime

Table 6. Maize yields.

Treatment	Season			
	Khwisero		Maseno	
	1	2	1	2
1. Control	0.55	0.16	0.89	0.55
2. 0 P + L	1.14	0.52	1.32	0.55
3. TSP (30 P kg ha^{-1})	0.53	0.00	0.68	0.87
4. TSP (30 P kg ha^{-1})+ L	2.48	1.74	1.71	1.46
5. FYM (30 P kg ha^{-1})	2.30	1.38	1.91	2.52
6. FYM (30 P kg ha^{-1}) + L	2.35	1.02	2.40	2.76
7. TSP (60 P kg ha^{-1})	0.72	0.00	1.55	0.73
8. TSP (60 P kg ha^{-1})+ L	3.30	1.52	1.99	0.98
9. FYM (60 P kg ha^{-1})	2.09	1.99	2.89	3.20
10. FYM (60 P kg ha^{-1}) + L	4.49	3.13	4.26	3.32
11. TSP (30 P)+ FYM (30 P)	2.60	1.30	2.03	1.83
12. TSP (30 P)+ FYM (30 P)+ L	2.38	2.79	3.04	2.35
LSD	0.76	0.31	0.81	0.85
%CV	21	13.9	23	27

gave significantly higher maize yields than the lower rate (30 P ha^{-1}) at both sites in both seasons.

The yields in the second season were lower than the first season for all treatments at Khwisero except two; sole application of lime and TSP (30 P) + FYM (30 P) + L. At Maseno, four treatments (TSP (30 P kg ha^{-1}), FYM at both rates of 30 and 60 kg P ha^{-1}, and FYM (30 P kg ha^{-1}) + L) had higher yields in the second than the first season. The residual yields as determined by the difference between the treated soils and the control showed that the nutrients applied in the first season had an effect in the second. The order of the top three treatments in residual effects at Khwisero was: FYM (60 P kg ha^{-1}) + L (1856%), TSP (30 P) + FYM (30 P) + L (1644%) and FYM (60 P kg ha^{-1}) (1144%), while at Maseno they were: FYM (60 P kg ha^{-1}) + L (5044%), FYM (60 P kg ha^{-1}) (482%), and FYM (30 P kg ha^{-1}) + L (402%).

Correlations between exchangeable acidity and maize yields

In order to determine which of the measured soil properties were related to the observed maize yields, correlation and regression analyses were conducted. Soils sampled at 9 WAP were used to obtain correlations with the first-season maize yields while those sampled at 21 WAP of first-season crop (beginning of second season) were used to compute the correlations of the relevant parameter with the second-season maize yields. There was a significant negative correlation between exchangeable acidy and maize yields when all the twelve treatments, or when treatments with no lime were used in the correlation analysis at Khwisero in both seasons. (Table 7). However, when only treatments with lime were used in the analysis, there was no correlation between exchangeable acidy and maize yields at both sites. At Maseno, there was no significant relationship between exchangeable acidity and maize yields when all treatments, or treatments with lime were used in the analyses but when treatments with no lime were used, there was a significant negative correlation in the first season (Table 7). However, in the second season, there was no significant correlation between exchangeable acidity and maize yields at Maseno.

There was no correlation between available P and maize yields at Khwisero, when all treatments, or when lime treatments with no lime, were used in the analysis, in both seasons. However, when only those treatments that were limed were used in the analysis, there was a significant positive correlation between available P and maize yield at this site in both seasons (Table 7). At Maseno, there was no significant correlation between available soil P and maize yields in both seasons irrespective of whether lime or non-lime treatments were used in the analyses (Table 7).

DISCUSSION

Both lime and FYM increased the soil pH and reduced exchangeable acidity but lime was much more effective in both aspects. The increase in pH and a concomitant decline in exchangeable acidity with the application of lime is to be expected. The hydroxyl ions produced by the reaction of calcium carbonate in soil neutralize the H^+ therefore increasing the pH while at the same time reacting with Al^{3+} to form $(OH)_3$ which is precipitated and

Table 7. Relationships between exchangeable acidity and available soil phosphorus with maize yields at Khwisero and Maseno.

Parameter	Site	Season	R^2	Equation
Exchangeable acidity (all treatments)	Khwisero	1	0.44**	y = -1.56x + 2.91
Exchangeable acidity (treatments with no lime)	Khwisero	1	0.94***	y = -4.93x + 6.41
Exchangeable acidity (treatments with lime)	Khwisero	1	0.12^{NS}	y = -33.22x + 5.07
Exchangeable acidity (all treatments)	Maseno	1	0.23 S	y = -1.26x + 2.65
Exchangeable acidity (treatments with no lime)	Maseno	1	0.76**	y = -14.42x + 13.62
Exchangeable acidity (treatments with lime)	Maseno	1	0.22^{NS}	y = -16.28x + 4.30
Exchangeable acidity (all treatments)	Khwisero	2	0.35*	y = -1.15x + 1.99
Exchangeable acidity (treatments with no lime)	Khwisero	2	0.98***	y = -5.93x + 7.30
Exchangeable acidity (treatments with lime)	Khwisero	2	0.01^{NS}	y = 3.42x + 1.43
Exchangeable acidity (all treatments)	Maseno	2	0.05^{NS}	y = -0.57x + 2.03
Exchangeable acidity (treatments with no lime)	Maseno	2	0.44^{NS}	y = -8.75x + 9.06
Exchangeable acidity (treatments with lime)	Maseno	2	0.17^{NS}	y = -25.53x + 4.67
Available P (all treatments)	Khwisero	1	0.20^{NS}	y = 0.24x + 0.36
Available P (treatments with no lime)	Khwisero	1	0.08^{NS}	y = 0.10x + 0.79
Available P (treatments with lime)	Khwisero	1	0.54*	y = 0.45x - 0.71
Available P (all treatments)	Maseno	1	0.17^{NS}	y = 0.24x - 0.13
Available P (treatments with no lime)	Maseno	1	0.09^{NS}	y = 0.11x + 0.65
Available P (treatments with lime)	Maseno	1	0.36^{NS}	y = 0.53x - 2.83
Available P (all treatments)	Khwisero	2	0.28^{NS}	y = 0.45x - 1.57
Available P (treatments with no lime)	Khwisero	2	0.13^{NS}	y = 0.23x - 0.70
Available P (treatments with lime)	Khwisero	2	0.70*	y = 0.71x - 2.77
Available P (all treatments)	Maseno	2	0.03^{NS}	y = 0.12x + 0.65
Available P (treatments with no lime)	Maseno	2	0.00^{NS}	y = 0.03x + 1.58
Available P (treatments with lime)	Maseno	2	0.05^{NS}	y = 0.16x + 0.08

NS = Not significant, *significant at $p < 0.05$, **significant at $p < 0.01$, ***significant at $p < 0.001$.

hence removed from the exchangeable sites (Caires et al., 2002; Hue, 2004; Goulding, 2016). This reduces the exchangeable acidity which is comprised of exchangeable Al^{3+} and H^+. Exchangeable acidity in tropical soils is however almost entirely due to Al^{3+} ions (Sanchez, 2019) hence a reduction in exchangeable acidity can be equated to a decrease of potential Al toxicity to crops.

The soils treated with lime maintained a pH of greater than 5.5, with low levels of exchangeable acidity up to 42 WAP. The residual effect of lime on soil acidity was therefore still apparent after two cropping seasons and can be utilized to plant another maize crop without the risk of aluminum toxicity. This is consistent with the findings of Kisinyo et al. (2014) who reported that residual effects of a similar amount of lime as that used in this study (4 t ha^{-1}) could be experienced six seasons after the initial application in western Kenya.

The increase in the soil pH by FYM, particularly at the higher rate of application can primarily be attributed to its high pH (8.3) at the time of application, due to the presence of calcium and magnesium elements in it (Tang et al., 2007; Hue et al., 1986). It may also partly be explained by proton (H^+) exchange between the soil and the added manure which during the initial decomposition, prior to its collection, may contain phenolic and humic-like material (Narambuye and Haynes, 2006; Wong et al., 1998; Tang et al., 1999). It is these organic anions that consume protons from the soil thus tending to raise the equilibrium pH. The observed reduction in exchangeable acidity due to application of FYM has also been reported by others (Ano and Ubochi, 2007; Onwuka, 2011). While the decrease in exchangeable acidity by lime is mainly a function of the rise of soil pH, which neutralizes OH^- and precipitates Al^{3+}, the same is not always true for OMs such as FYM. There are other mechanisms involved in the reactions of Al with OMs which probably involve complex formation with low molecular weight organic acids and humic material produced during the decomposition of the OMs and adsorption of Al onto the decomposing organic residues (Ritchie, 1994).

Available P generally increased with the P rate for both TSP and FYM treatments. However, all the treatments with P application of 30 kg^{-1} failed to attain the critical level of 10 mg P kg^{-1} (using the Olsen method) which is considered adequate for maize. The higher P rate of 60 P kg^{-1} is therefore appropriate for these P-deficient sites. The FYM was as effective as TSP in supplying available P for the crop especially at 21 WAP when most of the mineralization had occurred. This is consistent with earlier studies reported in the same region (Opala et al., 2012; Nziguheba et al., 2016). The residual effects of FYM on available P were stronger than TSP. For example, although statistical significance was not attained, sole FYM treatments had generally higher levels of available P than TSP at comparable P rates at 42 WAP. Furthermore, it is only treatments with FYM when applied with lime (FYM + lime 60 P ha^{-1}), or with TSP and lime (FYM +TSP+ lime) that had significantly higher available soil P than the control at both sites at 42 WAP. The ability of the FYM treatments to maintain higher levels of available P in the soil compared to TSP can be attributed partly to the ability of organic materials such as FYM to reduce the P fixation capacity of soils. It has been reported that organic materials especially at high rates of application reduce P fixation through a variety of mechanisms such as chelation of Al, increasing pH, and competing for the P sorption sites (Cong and Merckx, 2005; Guppy et al., 2005; Whalen and Chang, 2002). Therefore, combining FYM with TSP has the advantage of maintaining the soluble P longer in the available forms.

Application of lime with no P inputs generally failed to significantly increase maize grain yields above the control. This is attributed to its failure to significantly increase the initial low soil P levels (4.57 mg kg^{-1} at Khwisero and 7.41 mg kg^{-1} at Maseno) at these sites. Conversely, sole application of FYM increased yields because of the nutrients it contained (Table 3) and its ability to reduce soil acidity. In addition, FYM confers other advantages associated with organic materials such as improving soil structure and moisture retention, reducing P fixation and enhancing biological activities (Gurmu, 2020; Craswell and Lefroy, 2001). FYM and lime gave similar yields when they were applied in combination with TSP in the first season, at similar P rates. This was despite FYM being less effective in increasing pH than lime, and therefore presumably less effective in reducing Al toxicity. However, it has been reported that FYM can reduce Al toxicity through other mechanisms such as chelation of Al, without increasing the pH, therefore providing a conducive environment for maize growth (Opala et al., 2010).

The yields in the second season were generally lower than the first for most of the treatments because no nutrient inputs were applied in the second season. The crop therefore likely suffered nutrient deficiencies because the initial soil fertility of the sites was poor (Table 1). The higher yields in Maseno compared to Khwisero in the second season are attributed to the better rainfall in this ‘short rains’ season at this site compared to Khwisero. In addition, the initial fertility status at Maseno, although poor, was generally better than that at Khwisero (Table 1). The mean residual exchangeable acidity at Maseno (0.48 cmol kg^{-1}) as determined at the beginning of the second season (21 WAP of first crop) was also lower than that at Khwisero (0.67 cmol kg^{-1}), hence maize growth in most treatments at Khwisero is likely to have been more constrained by Al toxicity in this season than at Maseno.

Triple superphosphate when applied at 30 or 60 kg P ha^{-1}, with no lime or FYM failed to significantly increase maize yields compared to the control despite the significantly higher levels of available soil P in these treatments than the control. This is attributed to possible Al toxicity which inhibited the crop from utilizing the available P together with other nutrients because, at both sites, the soil pH was below 5.5 and with high exchangeable acidity. When TSP was combined with lime or FYM the deleterious effects of acidity were ameliorated and maize responded to the applied fertilizer, with generally higher yields at the higher P rate, particularly at Khwisero, where the negative effect of soil acidity on maize yields was more severe than at Maseno (Table 7).

There was no correlation between the available P and maize yields in both seasons irrespective of whether or not lime was applied at Maseno, signifying that factors other than acidity and available P were controlling the maize yields at this site. In particular, N is likely to have limited growth in the treatments without FYM in the second season**.** The better performance of FYM treatments, especially when combined with lime, compared with those with only inorganic fertilizers with lime at comparable P rates in the second season, is therefore mainly attributed to the residual N from FYM. In the first season, the FYM was applied to supply P at 30 and 60 kg P ha^{-1} and at these rates, the FYM supplied 127 and 254 kg N ha^{-1} respectively. Nitrogen recommendation for maize in the study area is only 100 kg N ha^{-1} hence the excess N supplied with FYM, coupled with the fact that FYM mineralizes slowly over time, contributed to the strong residual effects observed in FYM treatments. Treatments with TSP, on the other hand, were in the first season supplied with 100 kg N ha^{-1} as CAN, which is soluble and hence easily leached or lost through runoff. The residual effect of CAN is therefore not high and hence the poor performance of treatments that were supplied with N from CAN in the second season.

The superior maize yields in both season at both sites, obtained from a combination of lime and FYM at the higher P rate (FYM + lime at 60 kg P ha^{-1}), seems to be due to synergistic effects with the fast-acting lime immediately ameliorating soil acidity and maintained the suitable conditions for a long time while FYM, due to synchronized mineralization, provided the nutrients over the two seasons. This is in contrast to FYM with TSP at similar P rates where the effectiveness of the FYM manure in reducing acidity in the second season could have declined leading to ineffective utilization of the residual P. Similarly, TSP applied with lime at similar rates of P (60 kg P ha^{-1}) lacked the advantages provided by FYM, besides nutrients and the residual N in the second season.

Conclusion

The application of lime was more effective in increasing the soil pH and decreasing exchangeable Al compared to FYM. Sole application of lime did not however increase yields compared to the control with no nutrient or lime inputs. Similarly, the sole application of TSP also failed to significantly increase yields especially, at Khwisero likely due to Al toxicity. When TSP was combined with lime or FYM manure, the harmful effects of soil acidity were mitigated and maize responded to the applied fertilizers. Sole application of FYM manure significantly increased maize yields above the control treatment due the nutrients it contained and its ability to reduce Al toxicity. Application of FYM with lime at the higher P rate of 60 kg ha^{-1} had the highest maize grain yields at both sites in both seasons. Farmyard manure treatments had strong residual effects on maize yields compared to inorganic fertilizers (TSP + CAN) which did not show significant residual effects. Phosphorus applied at 60 kg ha^{-1} generally gave a higher yield than 30 kg ha^{-1} as long as acidity had been overcome by liming or application of FYM. For higher immediate and residual maize yields, combining lime with FYM applied at a P rate of 60 kg ha^{-1} seems to be a promising strategy to overcome soil acidity and P deficiency at these sites.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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