

Research paper

COMPARATIVE EFFECTS OF SOIL AMENDMENTS ON PHOSPHORUS USE AND AGRONOMIC EFFICIENCIES OF TWO MAIZE HYBRIDS IN ACIDIC SOILS OF MOLO COUNTY, KENYA

Richard N. Onwonga¹, Joyce J. Lelei², Joseph K. Macharia²

¹⁺Department of Land Resource Management and Agricultural Technology, University of Nairobi. P.O. Box 29053, Nairobi.

²Department of Crops, Horticulture and Soils, Egerton University. P.O. Box 536, Egerton.

ABSTRACT

The deficiency of P and the shortened growing season due to climate change, are identified constraints in the production of commonly grown long maturing maize hybrid (H614) in the acid soils of Molo County. The current study investigated (i) the effect of soil amendments; lime (L), minjingu phosphate rock (MPR) and manure (FYM), on soil available P and its uptake, phosphorus use efficiency (PUE) and maize grain yield of long (H614) and short (H513) maturing maize hybrids and (ii) the relative agronomic efficiency (RAE) of MPR. Field experiments were set up at the Kenya Agricultural Research Institute, Molo during the long rain seasons of 2009 and 2010. A randomized complete block design with a 2³ factorial arrangement was used for the first objective. The factors, each at two levels, were L (0 and 3 t ha⁻¹), MPR (0 and 60 kg P ha⁻¹) and FYM (0 and 5 t ha⁻¹) giving a total of eight treatments; C (control), L, MPR, FYM, L+MPR, L+FYM, MPR+FYM and L+MPR+FYM. The relative agronomic efficiency (RAE) of MPR was determined in a parallel experiment laid out in randomized complete block design with a split plot arrangement and replicated thrice. Maize hybrids H513 and H614 were the test crops (for the two objectives) and constituted the main plots. The split plots were an absolute control and 60 kg P ha⁻¹ each of triple super phosphate (TSP) and MPR. Soil available P and its uptake, PUE, RAE and maize yields were measured. The application of soil amendments increased soil available P and its uptake, PUE and maize yields over the control for both maize hybrids. Highest values of the measured parameters were recorded in the L+MPR+FYM treatment and maize hybrid H614. The two year mean values of relative agronomic efficiency RAE (%) of MPR were 60 (H513) and 66.7 (H614), and significantly higher in the H614. The combined application of the soil amendments could improve maize productivity and is recommended for the acid soils of Molo County. The maize hybrid H513 though with lower yields, matured faster than H614 and would thus come in handy as an adaptation strategy in the face of climate change and variability.

Key words: Climate change; Farm Yard Manure; Maize hybrids H513 and H614; Minjingu Phosphate Rock; soil acidity

1.0 INTRODUCTION

About 80% of African soils have inadequate amounts of phosphorus (P), an element essential for sustaining and increasing crop production, and its deficiency is a production constraint in several areas of East Africa (FAO, 2004, Onwonga et al., 2008). The deficiency is largely due to low

occurrence of P-containing minerals (Nyandat, 1981; Bunemann, 2003), P-fixation in acid soils (Van der Eijk, 1997) and continuous cropping without commensurate nutrient replenishment (Sanchez, 2002; Bunemann, 2003; FAO, 2004).

Application of large amounts of inorganic fertilizer to supply P and additionally quench the P sorption capacity of the high P fixing acid soils, as is the case for Molo county, and avail the excess P in soil (Hue et al., 2001) is impractical for the impoverished smallholder farmers (Onwonga et al., 2008). The application of mineral fertilizers has also been reported to have negative environmental consequences such as nutrient immobilization and ground water pollution (Myint et al., 2010; Ginkel, 2011). To improve productivity of the acid soils, rebuilding soil P fertility in a feasible and environmentally friendly manner is imperative. This can be achieved by the application of soil amendments such as phosphate rocks (PRs), lime and manures (Sokora, 2002).

Minjingu Phosphate Rock (MPR) is the predominant type of PR deposit in Eastern Africa with sufficient quantity and reactivity cum potential for direct application (Okalebo et al., 2006). The direct application of phosphate rock supplies P, and reduces dependency on expensive imported fertilizers (Sokora, 2002; Okalebo et al., 2006). Increased yields have been reported where MPR has been used as a source of P to crops (Mathur and Suresh, 1989; Szilas et al., 2007). Lime, on the other hand, reduces the activity of Al ions resulting in increased extractable P (Barber et al., 1963; Sanchez and Uehara, 1980). Kisinyo et al. (2005) and Gudu et al. (2005) reported increases in available P in soils and shoot P after liming acid soils of Uasin Gishu County, located in the Rift Valley Province of Kenya.

Organic manures supplies plant nutrients such as P through decomposition (Wuta and Nyamugafata, 2012) and the organic acids produced in the process chelate P-fixing elements in the rhizosphere or decomposition system (Fox and Comerford, 1990). Opalla et al. (2013) reported increased available P in acid soils of Bukura and Kakamega in Western Kenya with application of farm yard manure (FYM).

The application of soil amendments in improving maize production has to take cognisance of the current climate change scenario. There exists overwhelming evidence of climate change in Kenya with likely impact in the production of maize (Mati, 2000; Patz et al., 2005). One of the evidences observed in Molo County is reduced rainfall leading to shortened growing seasons (Kingston et al., 2007; Ambrose and Sikes, 1991). An adaptation strategy is therefore required and this would involve the introduction of short maturing maize Hybrid (H513), alongside the long maturing and commonly grown maize Hybrid H614 (Mati 2000). There is however a dearth of literature on comparative response of the two maize hybrids to application of soil amendments particularly with regard to; soil available P and, uptake and yields of the maize hybrids. This is in addition to phosphorus use and agronomic efficiencies and thus necessitating the current study.

2.0 MATERIALS AND METHODS

2.1 Site description

The study was carried out at the Kenya Agricultural Research Institute (0°1'S, 35°41'E, 2500m asl) which is situated in Molo County, Kenya. The County is categorized in the medium to high potential agro ecological zone of Kenya (Jaeztold et al., 2007). The rainfall pattern is bimodal

with the long rain season (LRS) occurring from March to August and the short rain season (SRS) from September/October to December. The respective mean annual rainfall amounts received in 2009 and 2010, when the experiment was conducted, were 917 and 1120 mm. The soils are acidic, with top soil (0-20 cm) pH (H₂O) of 4.7 and available P content of 2.7 mg kg⁻¹ (Table 1) which are rated as low (Landon, 1991). The top soil had low levels of N (0.18 %) but medium in the contents of exchangeable bases (K, 0.7; Mg, 0.8 and Ca, 9.6 cmol_ckg⁻¹) and CEC (20.3 cmol_ckg⁻¹) according to Landon (1991) classification levels for different elements in soil. The soils are well drained, deep, dark reddish brown with a mollic A horizon and are classified as Mollic Andosols (Jaetzold et al., 2007).

Table 1: Some physical and chemical properties of soils (0-60 cm depth)

Soil property	Soil Depth (cm)			Soil property	Soil Depth (cm)		
	0-15	15-30	15-30		0-15	15-30	15-30
Exc. Al (cmol _c kg ⁻¹)	19.8	19.3	18.9	pH KCl	4.1	4.2	4.2
% N	0.18	0.15	0.15	Organic C (%)	1.4	0.9	0.8
P (mg kg ⁻¹)	2.7	2.8	5.8	Ca (cmol _c kg ⁻¹)	9.6	7.6	8.9
K cmol _c kg ⁻¹)	0.7	0.6	0.5	Mg (cmol _c kg ⁻¹)	0.8	0.7	0.8
%C	2.0	1.8	1.8	%sand	35.8	34.2	35.0
CEC (cmol _c kg ⁻¹)	20.3	19.3	18.7	% silt	28.3	30.0	28.3
Mineral N (mg kg ⁻¹)	21.1	33.4	27.9	% clay	35.8	36.2	36.7
pH water	4.7	4.9	4.8	Textural class	clay loam (across depths)		

2.2 Treatments and Experimental Design

A randomized complete block design with a 2³ factorial arrangement was used to determine the effect of lime (L), manure (FYM) and minjingu phosphate rock (MPR) on soil available P and its uptake and the performance of the two (H513 and H614) maize hybrids,. The factors each at two levels were; lime (0 and 3 t ha⁻¹), MPR (0 and 60 kg P ha⁻¹) and FYM (0 and 5 t ha⁻¹) giving a total of eight treatments; control (C), lime (L), MPR, FYM, L+MPR, L+FYM, MPR+FYM, and L+MPR+FYM. The treatments were applied to the two maize varieties, H513 and H614, which were planted in separate experiments.

To determine the relative agronomic efficiency (RAE) of MPR, a parallel experiment was laid out in a randomized complete block design with a split plot arrangement and replicated thrice. The two maize hybrids, H513 and H614, constituted the main plots. The split plots were an absolute control and 60 kg P ha⁻¹ each of TSP and MPR.

2.3 Agronomic practices

Land was prepared manually using hand hoes. L and MPR were broadcasted and incorporated to soil depth of 15 cm two weeks prior to planting. FYM was applied in the planting holes and mixed well with the soil a week prior to planting. TSP was applied by banding at planting. To eliminate possible deficiency of the commonly limiting nitrogen (N) nutrient, Calcium Ammonium Nitrate (CAN) fertilizer was applied to all treatments as a top dress, at the rate of 60 kg ha⁻¹. The maize hybrids; H614 and H513 were sown at the rate of two seeds per hill in the long rain season of 2009 and 2010, at spacing of 30 x 75 cm. Thinning to one plant per hill was

done a month after planting. Standard cultural practices such as weeding, pest and disease control were carried out uniformly in all plots (Jugenheimer, 1985).

2.4 Sampling of Soils, Plants and Farmyard Manure

Soil sampling: Composite soil samples to determine the initial chemical and physical properties of the soil were collected from six profile pits at three soil depths (0-15, 15-30 and 30-60 cm) before application of the treatments. Thereafter soil samples were collected from the top soil (0-15 cm) at seedling, tasseling and maturity stages of maize growth to monitor changes in soil available P. The samples were obtained randomly from four locations in each plot between the plants within a row and bulked to get one composite sample.

Plant sampling: At seedling four whole plants were sampled randomly, while at tasseling, the leaf opposite the ear was sampled from ten randomly selected plants. At physiological maturity of maize, the above ground portion of the plant was harvested from the three centre rows and divided into stover (stalk and leaves), cob and grains. The plant samples collected at seedling, tasseling and harvest (stover) were chopped into small pieces and sub-samples oven dried at 65°C for 72 hours. The weights of the oven dry subsamples were recorded and used to calculate the total above-ground dry matter yields.

Farm Yard Manure: Approximately 1 kg FYM was collected from the source (Tatton demonstration Unit of Egerton University) at approximately 45 cm from the surface of the heaps and stored in plastic bags. They were air dried and ground to pass through a 2mm sieve. The manure was analyzed for Total N, organic C, available P, K, Ca, Mg and S.

2.5 Laboratory Analysis of Soils, Plants and Farmyard Manure

Standard laboratory procedures were followed in analyzing the nutrient contents of the soil and plant samples and the FYM. Air - dried soils sieved through 2 mm mesh were analyzed for pH (Soil: H₂O and KCL: 1:2.5), texture (hydrometer method), total N (Kjedahl method) total carbon (Walkley- Black, 1934), Exchangeable Al (McLean, 1965), CEC (Chapman, 1965), mineral N and available P according to Okalebo et al. (2002). Exchangeable bases (K, Ca and Mg) were extracted with 1.0 M-ammonium acetate at pH 7 and measured by atomic adsorption spectrophotometry. Plant samples were ground and passed through 2 mm sieve and their P content analyzed according to Okalebo et al. (2002) to determine nutrient uptake. The N, organic C, available P, K, Ca, Mg and S contents in the FYM were determined according to methods described by Okalebo et al., (2002).

2.6 Calculation procedures and statistical analysis

Nutrient uptake: The total nutrient uptake was calculated at the three maize growth stages using the following formulae (Peterburgski, 1986);

$$\text{Total nutrient uptake} = \text{nutrient concentration} \times \text{dry matter yield} \dots\dots\dots(1)$$

Maize yield: Maize from three middle rows of each plot was harvested, dehusked, dried, threshed and weighed. Grain yield (adjusted to 13% moisture content) was recorded and converted to kg ha⁻¹ using the following formula;

$$\text{Grain yield (kg ha}^{-1}\text{)} = \text{kg grain yield m}^{-2} \times 10,000\text{m}^2 \dots\dots\dots(2)$$

The agronomic P use efficiency: The agronomic P use efficiency was calculated as the yield obtained from the P (Yp) fertilized plot minus control (Yc), divided by a unit weight of the applied P fertilizer (Pw):

$$\text{PUE} = (\text{Yp}-\text{Yc})/\text{Pw} \dots\dots\dots(3)$$

Relative agronomic efficiency: The relative agronomic efficiencies (RAE) was computed as; the ratios of the yield responses with test fertilizer (MPR) to the respective yield responses of the reference fertilizer (TSP) at the same rate (60 Kg P ha⁻¹), i.e.

$$\text{RAE} = [(y_{\text{MPR}} - y_{\text{control}} / y_{\text{TSP}} - y_{\text{control}}) \times 100] \%, \dots\dots\dots(4)$$

Where y is yield of maize in response to the various treatments

Statistical analysis

Analysis of variance (ANOVA) procedures using SPSS (1999) were used to detect statistical variation in treatment effects on maize grain yield, P uptake and available P, at P=0.05 level of significance, while Tukey's Honestly Significant Difference was used for mean separation. Paired sample t tests were used to compare grain yield, P uptake and available P mean values of H513 and H614, as affected by the treatments. Correlations between available soil P and grain yield, P uptake and grain yield, and P available in the soil and uptake were measured.

3.0 RESULTS AND DISCUSSION

3.1 Chemical Composition of Farmyard Manure

The farm yard manure (FYM) applied, initially stored under shade, had high contents of essential macronutrients N, K, Ca, Mg and S and was low in available P (Table 2). Good management practices of FYM minimize the loss of nutrients and organic matter (Motavali, 1994) and could potentially improve soil productivity and fertility and consequently the yield of crops (Venek et al. 2003). The low available P content was due to the fact that much of the P is in unavailable forms and become slowly available to the crop during the growing season to which it is applied as well as to subsequent crops through residual effect (Negassa et al., 2005).

Table 2 Chemical composition and Nutrient quantity (kg) in 5 t/ha of the FYM

	Total N	Org. C	P	K	Ca	Mg	S
Chemical Composition	1.4 (%)	0.8 (%)	64 (mg kg ⁻¹)	2450 (mg kg ⁻¹)	570 (mg kg ⁻¹)	5870 (mg kg ⁻¹)	700 (mg kg ⁻¹)
Nutrient quantity (kg)	70	40	0.32	12.3	2.9	29	3.5

3.1 Soil available P at different stages of plant growth

212 The available P content in the soil generally declined with progression of maize growth and was
213 lowest in the control treatment (Table 3). In terms of season, higher amounts of available P in the
214 soil across hybrids and treatments were found in the second year (Table 3).
215

216 **Table 3: Means of Soil Extractable P (mg kg⁻¹) during plant growth**

Treatment	H614								H513							
	2009				2010				2009				2010			
	Seed	Tass	Mat	Aver	Seed	Tass	Mat	Aver	Seed	Tass	Mat	Aver	Seed	Tass	Mat	Aver
C	2.8 ^e	1.5 ^f	1.1 ^e	1.8	1.6 ^f	1.2 ^e	0.8 ^f	1.2	2.6 ^f	1.9 ^e	1.3 ^e	1.9	1.7 ^g	1.4 ^d	1.2 ^d	1.4
L	7.9 ^d	4.2 ^e	3.8 ^d	5.3	6.6 ^e	6.8 ^d	2.4 ^e	5.3	7.5 ^e	5.5 ^d	4.1 ^d	5.7	6.1 ^f	7.4 ^c	3.1 ^c	5.5
RP	10.9 ^d	8.2 ^{bc}	7.6 ^b	8.9	14.9 ^{cd}	10.2 ^{bc}	7.9 ^{cd}	11.0	11.1 ^d	9.2 ^{bc}	7.5 ^{bc}	10.2	13.7 ^{de}	10.9 ^b	9.6 ^b	11.4
FYM	12.5 ^{cd}	5.5 ^d	3.1 ^d	7.0	11.5 ^d	8.2 ^{cd}	3.8 ^e	7.8	13.4 ^{cd}	6.6	3.8 ^d	7.9	12.1 ^e	9.1 ^{bc}	4.7 ^c	8.6
L+RP	15.8 ^c	10.3 ^{ab}	7.6 ^b	11.2	17.7 ^b	12.8 ^{ab}	8.8 ^{bc}	13.1	15.1 ^c	11.1 ^{ab}	8.6 ^b	11.6	18.4 ^{bc}	14.9 ^a	9.1 ^b	14.1
L+FYM	15.2 ^c	7.2 ^{cd}	5.8 ^c	9.4	15.6 ^{bc}	9.8 ^c	6.8 ^d	10.7	15.7 ^c	8.8 ^c	6.2 ^c	10.2	16.1 ^{cd}	10.4 ^b	8.9 ^b	11.8
RP+FYM	19.2 ^b	11.4 ^a	6.9 ^{bc}	12.5	16.4 ^{bc}	13.1 ^a	8.2 ^b	12.6	20.1 ^b	11.6 ^{ab}	7.4 ^{bc}	13.0	21.7 ^{ab}	15.6 ^a	9.9 ^b	15.7
L+RP+FYM	23.1 ^a	12.6 ^a	9.9 ^a	15.2	20.7 ^a	13.5 ^a	11.1 ^a	15.1	24.7 ^a	13.4 ^a	10.6 ^a	16.2	22.9 ^a	15.8 ^a	13.7 ^a	17.5
Average	13.4	7.6	5.7	8.9	13.1	9.5	6.2	9.6	13.8	8.5	6.0	9.6	14.1	10.7	7.5	10.8

217 Key: Seed= seedling; Tass= tasseling; Mat= maturity; Aver = average

218 Means in a column followed by the same letter are not significantly different ($P<0.05$)

In the year 2009, significantly higher amounts of available P (ppm) were found with combined application of soil amendments (15.2-23.1) than in sole application of treatments (7.9-12.5) for H614 at seedling. The level of soil available P followed the order; L+MPR+FYM > MPR+FYM > L+MPR = L+FYM (Table 3). For H513, significantly higher (24.7) soil available P was found in the L+MPR+FYM treatment at the seedling stage of maize growth. During maize tasseling, for both H614 and H513, the combined treatments, L+MPR+FYM (12.6, 13.4), MPR+FYM (11.4, 11.6) and L+MPR (10.3, 11.1), had significantly higher amounts of P. At the physiological maturity of maize, the available P in the soil was significantly higher in the L+MPR+FYM treatment for both maize hybrids, (Table 3).

In the second year, significantly higher (20.7) amounts of soil available P (ppm) were obtained in the L+MPR+FYM treatment (Table 3) for maize hybrid H614 at seedling stage of maize growth. For hybrid H513 significantly higher amounts of available P were found in the L+MPR+FYM (22.9) and MPR+FYM (21.7) treatments at seedling stage of maize growth. At the tasseling stage, L+MPR+FYM (13.5, 15.8), MPR+FYM (13.1, 15.6) and L+MPR treatments (12.8, 14.9) had significantly higher amounts of soil available P for both maize hybrids H513 and H614. At maize maturity, significantly higher amounts of soil available P (ppm) were found in the L+MPR+FYM treatments (11.1, 13.7) for both H513 and H614, respectively (Table 3).

A paired samples *t* test failed to reveal a statistically reliable difference between soil available P content in H513 ($M = 5.25$, $s = 3.62$) and H614 ($M = 5.72$, $s = 2.87$) at physiological maturity of maize, $t(7) = 0.465$, $p = .656$, $\alpha = .05$ in the year 2009. In the second year however, the soil available P content was significantly higher in the maize hybrid H513 ($M = 7.52$, $s = 4.14$) than H614 ($M = 6.22$, $s = 3.53$) at the physiological maturity of maize, $t(7) = 4.4$, $p = .03$, $\alpha = .05$.

The decline in soil available P with plant growth can be attributed to crop uptake which is usually continuous throughout crop growth. Maize draws most nutrients from the soil from about 10 days before tasseling to about 25-30 days after tasseling (Odhiambo, 1989, Lelei, 2006). The lower available P content in the soil in the control treatment (Table 3) could be attributed to fixation due to the low pH level (soil pH (H_2O) < 4.7) and lack of application of the soil acidity ameliorating amendments. The P deficiency observed in acid soils is often associated with high P fixation and severe soil acidity (Mokwunye et al., 1996). Holford (1997) reported that in soil, more than 80% of the P becomes immobile and unavailable for plant uptake because of adsorption, precipitation, or conversion to the organic form. P uptake rates are highest between pH 5.0 and 6.0 where $H_2PO_4^-$ dominates (Ullrich-Eberius et al., 1984; Furihata et al., 1992).

Similarly, the higher levels of P in the treatments containing the amendments L, MRP and FYM than in the control could be attributed to their supply of P. The FYM, for instance, increases available P in the soil through chelation and decomposition (Oberson et al., 1993). The decomposition products of organic materials have significant chelation capacity that lowers the activity of polyvalent cations (Ca, Fe, and Al) which form insoluble salts with P and so liberate phosphorus. Several authors (Violante and Gianfreda, 1993; Staunton and Leprince 1996; Geelhoed et al., 1999) have reported that amendment with organic residues may influence P dynamics in soils by means of competition between low-molecular-weight organic acids and phosphates for sorption sites that usually favours adsorption of organic acids and delays P adsorption. Braschi et al. (2003) reported that different rates of organic matter addition increased

extractable P at different soil-moisture regimes by inhibiting P insolubilization whereas the adsorption process was not affected.

Nekesa et al. (2005) reported that treatments with a component of lime seemed to avail more P in the soil. They observed much higher available P in the soil at planting time for the second season and attributed it to the lime component both in MPR and agricultural lime that could have made the fixed P in the soil more available. Ndungu et al. (2006) reported that soil available P increased significantly following application of MPR. The higher amounts of soil available P in the 2010 season than in the first year may have been due to the residual effects of the amendments lime, FYM and MPR. According to Rowell (1994), the rapid adsorption of P on to soil particle surfaces is followed by a slower conversion into less available forms including mineral phosphates, thus P in the MPR and most phosphate fertilizers is available in the first season after application but remains over long periods of time hence their residual effects. Negassa et al. (2005) studying the integrated use of farmyard manure and NP fertilizers for maize in Oroma, Ethiopia, reported that FYM had significant residual effect on grain yield.

The combined treatments (L+MPR+FYM, MPR+FYM, L+MPR, L+FYM) were more beneficial in availing P in the acidic soil. The more pronounced effect of the amendments when applied in combination, especially L+MPR+FYM, may have been as a result of priming effect especially where FYM was present. Other workers have reported that PR applied alone did not enhance the performances of the test crops (Adediran et al., 1998; Tossah, 2000; Kolawole and Tian, 2007). Bezzola et al. (1994) reported that plant readily available, labile and moderately labile P fractions were improved when PR was applied in combination with plant residues.

3.2 Plant P uptake at different stages of plant growth

The uptake of P by maize generally increased from the seedling to tasseling growth stages and declined thereafter towards maturity across the treatments and hybrids (Table 4). The uptake was higher in the treatments where amendments L, MRP and FYM had been applied than the control. The P uptake (mg/g) in 2009, was significantly higher in the L+MPR+FYM (2.2) and MPR+FYM (2.1) treatments for maize hybrid H614 at seedling (Table 4). At the tasseling stage it was higher in the L+MPR+FYM treatments (2.9). At maturity there were no significant differences in P uptake in all treatments except for the control (0.3) which had the least P uptake (Table 4). Significantly higher amounts of P were registered in the L+MPR+FYM (2.7) treatment in the year 2010 for maize hybrid H614 at the seedling stage. At maize tasseling, the uptake was significantly higher in the treatments L+MPR+FYM (4.1), L+MPR (3.9) and L+FYM (3.8). At this stage the aforementioned combined treatments had higher uptake of P than when applied singly. At maize maturity the control, lime and MPR treatments had significantly lower P uptake than other treatments with the control having least uptake (Table 4).

The L+MPR+FYM treatment had significantly higher uptake of P (Table 4) for the maize hybrid H513, at the seedling stage of maize growth for both years. At tasseling stage, all the combined treatment (L+MPR+FYM, MPR+FYM, L+MPR, L+FYM) application recorded significantly higher P uptake in all years. At the maturity of maize for both years, the control had significantly lower P uptake.

310 **Table 4 Means of plant P uptake (mg/g) during plant growth**

Treatment	H614								H513							
	2009				2010				2009				2010			
	Seed	Tass	Mat	Aver	Seed	Tass	Mat	Aver	Seed	Tass	Mat	Aver	Seed	Tass	Mat	Aver
C	0.7 ^e	1.8 ^d	0.3 ^b	0.9	0.4 ^f	1.1 ^d	0.2 ^c	0.6	0.5 ^e	1.0 ^c	0.1 ^b	0.5	0.3 ^f	0.6 ^d	0.1 ^b	0.3
L	1.0 ^d	2.8 ^{ab}	1.2 ^a	1.7	1.1 ^e	2.9 ^c	1.1 ^b	1.7	0.8 ^d	2.0 ^{ab}	1.0 ^a	1.3	1.0 ^e	2.4 ^c	1.1 ^a	1.5
RP	1.1 ^d	2.3 ^c	1.1 ^a	1.5	1.6 ^d	2.9 ^c	1.1 ^b	1.9	0.9 ^d	1.5 ^b	0.9 ^a	1.1	1.5 ^{de}	2.4 ^c	1.0 ^a	1.7
FYM	1.4 ^c	2.4 ^{bc}	1.2 ^a	1.7	1.3 ^e	3.2 ^c	1.2 ^{ab}	1.9	1.2 ^c	1.6 ^b	1.0 ^a	1.3	1.2 ^e	2.7 ^c	1.1 ^a	1.7
L+RP	1.6 ^{bc}	2.6 ^b	1.2 ^a	1.8	1.9 ^c	3.9 ^{ab}	1.3 ^{ab}	2.4	1.4 ^{bc}	1.8 ^{ab}	1.0 ^a	1.4	1.8 ^{cd}	3.4 ^{ab}	1.2 ^a	2.1
L+FYM	1.8 ^b	2.5 ^{bc}	1.2 ^a	1.8	2.1 ^{bc}	3.8 ^{ab}	1.4 ^a	2.4	1.6 ^b	1.7 ^{ab}	1.0 ^a	1.4	1.9 ^{bc}	3.3 ^{ab}	1.3 ^a	2.2
RP+FYM	2.1 ^a	2.6 ^b	1.1 ^a	1.9	2.3 ^b	3.6 ^b	1.2 ^{ab}	2.4	1.9 ^a	1.8 ^{ab}	0.9 ^a	1.5	2.2 ^b	3.1 ^b	1.1 ^a	2.1
L+RP+FYM	2.2 ^a	2.9 ^a	1.2 ^a	2.1	2.7 ^a	4.1 ^a	1.4 ^a	2.7	2.0 ^a	2.1 ^a	1.0 ^a	1.7	2.6 ^a	3.6 ^a	1.3 ^a	2.5
Average	1.5	2.5	1.1	1.7	1.7	3.2	1.1	2.0	1.3	1.7	0.9	1.3	1.6	2.7	1.0	1.8

311
312 Key: Seed= seedling; Tass= tasseling; Mat= maturity; Aver = average
313 Means in a column followed by the same letter are not significantly different ($P<0.05$)

A paired sample *t* test showed that the differences in P uptake by the two maize hybrids were statistically significant in the second year (2010). Uptake was higher in maize hybrid 614 ($M = 1.06$, $s = 0.311$) than H513 ($M = 0.87$, $s = 0.311$) at the physiological maturity of maize $t(7) = 7.0$, $p = .00$, $\alpha = .05$.

The observed increase in plant P uptake by maize from the seedling to the tasseling growth stage and variations across soil amendments, and seasons may similarly be explained as for section 3.1-on soil available P. Wasonga et al. (2008) observed that, sites with unfavourable growth conditions like the high Al saturation, the key fixer of P in acid soils is Al ion (Hue et al. 1986), resulted in relatively low P uptake. The increase in pH after application of lime and MPR (results not shown) may have caused an increase in the available P in soil. Haynes (1982) reported that the adsorption of phosphate generally decreases as the pH is raised by liming. Anetor and Akinrinde (2006) reported improved available P content in acid soils of Ikenne, Nigeria due to the release of P from sorption sites by lime reaction.

The high P uptake increase that was observed when manure was combined with PR than the single application of treatments was due to availability of other nutrients, especially N and Mg. Akande et al. (2005) observed that the complimentary application of sokoto and ogun rock phosphate with poultry manure increased the percent P content in maize. Bezzola et al., (1994) also reported little or no significant changes in yields and P uptake of test crops when PR was applied alone, in contrast to when PR was combined with some plant residues. According to Marschner (1986) and Negassa et al. (2005), FYM contains other nutrients such as N and S and improves soil physical properties. Uzoho and Oti (2005) reported that the efficient utilization of P depends also on the availability of other nutrients in addition to a good rooting medium.

The observed lower P uptake by maize hybrid H513 compared to H614 may point to differences in the internal P requirements. Maize varieties are known to vary in P uptake and utilization efficiencies (Nielsen and Barber, 1978; Duncan and Baligar, 1990; Horst et al., 1993; Machado et al., 1999). Genetic and physiological components of plants have pro-found effects on their abilities to absorb and utilize nutrients under various environmental and ecological conditions (Baligar, et al., 2001). Wasonga et al. (2008) also observed differences in P requirements by open pollinated maize varieties and hybrids. Al- Whaibi (1983) reported differences in tissue composition of N and P of date palm varieties suggesting a difference in N and P uptake due to hybrid.

3.3 Grain yields and agronomic phosphorus use efficiencies of maize hybrids

Maize grain yields were significantly greater in the second year across treatments and hybrids and higher in maize hybrid H614 than H513 (Table 5). For the H513 hybrid, the yield ($t\ ha^{-1}$) ranged from 0.9-2.1 in 2009 and 1.1 to 2.4 in the second year. For H614 it ranged from 1.9-3.9 and 1.7-4.1 in the first and second years, respectively (Table 5).

Table 5: Maize grain yield of maize hybrids as influenced by the application of amendments

Treatment	2009				2010			
	H513	H614	% IOC	% IOC	H513	H614	% IOC	% IOC

			H513	H614			H513	H614
C	0.9 ^d	1.9 ^e	0	0	1.1 ^e	1.7 ^e	0	0.0
L	1.4 ^c	3.2 ^c	55.6	68.4	1.6 ^{cd}	3.5 ^{bc}	45.5	105.9
MP	1.3 ^c	2.7 ^d	144.4	42.1	1.7 ^c	2.9 ^d	54.5	70.6
FYM	1.2 ^c	3.1 ^c	33.3	63.2	1.5 ^d	3.3 ^{cd}	36.4	94.1
L+MPR	1.9 ^{ab}	3.5 ^b	111.1	84.2	2.1 ^b	3.9 ^a	90.9	129.4
L+FYM	1.4 ^c	3.4 ^{bc}	55.6	78.9	1.8 ^c	3.6 ^b	63.6	111.8
MPR+FYM	1.7 ^b	3.2 ^c	88.9	68.4	2.1 ^b	3.4 ^{bc}	90.9	100.0
L+MPR+FYM	2.1 ^a	3.9 ^a	133.3	105.3	2.4 ^a	4.1 ^a	118.2	141.2
Average	1.5	3.1	65.3	63.8	1.8	3.3	62.5	94.1

Key: Seed= seedling; Tass= tasseling; Mat= maturity, IOC = increase over control

Means in a column followed by the same letter are not significantly different ($P < 0.05$)

The grain yields for the maize hybrid H614 were significantly higher in L+MPR+FYM (3.9) treatment in 2009 and in L+MPR+FYM (4.1) and L+MPR (3.9) treatments in 2010 (Table 5). In 2009 the maize hybrid H513 maize grain yields were significantly higher in L+MPR+FYM (2.1, 1.9) and L+MPR treatments while in 2010 it was significantly higher in the L+MPR+FYM (2.4) treatment. The control had the lowest yields in both years and maize hybrids. The differences in maize yield between the two hybrids were statistically significant in both years. The maize grain yield of H614 hybrid ($M = 3.1$, $s = 0.60$; $M = 3.3$, $s = 0.74$) was higher than for H513 ($M = 1.5$, $s = 0.39$; $M = 1.8$, $s = 0.41$) in the year 2009 ($t(7) = 14.1$, $p = .00$, $\alpha = .05$ and 2010, $t(7) = 9.5$, $p = .00$, $\alpha = .05$). The computed percentage increases in grain yield over the control were higher with treatment combination and generally higher for H614 than H513 (Table 5).

The higher grain yields in the second year, was partly as a result of the higher available P content in soil (section 3.1) due to residual effect of the amendments FYM and MPR (Buresh et al., 1997) and consequently uptake by maize (sections 3.1, 3.2). The lower yield in the control may be attributed to the low availability of P due to fixation in the acid soil. Phosphorus is the second most frequently limiting macronutrient for maize growth (Sanchez, 2002; Bunemann, 2003; FAO, 2004). Wasonga et al. (2008) observed lack of significant grain yield responses to P application rates beyond 13 kg P ha⁻¹ in acidic soil and attributed this to the high Al saturation. Reduced root volume as a result of Al toxicity has been reported to contribute to low dry matter production by Al sensitive varieties (Baligar et al., 1997).

The supply of P by the amendments especially when applied in combination (L+MPR+FYM) contributed to the maize grain yield increases. Valluru et al. (2010) reported about 50-105% increase in biomass yield of pear millet with P addition. Sholly et al. (2010) recorded about 29% yield increase with manure application in wheat. Ndung'u et al. (2006) reported significant increases in bean yields when 60 kg P ha⁻¹ as MPR was applied, contributing to a 260 % increase above the control. They also observed significant maize grain yield increases with sole application of MPR or in combination with fallow biomass as compared with treatments without external nutrient addition (control) or with fallow biomass alone in all seasons. Zafar et al. (2011) further observed that the ability of an organic material to lower the exchangeable Al is more important in increasing maize yields than its ability to increase P availability. The higher grain yields in H614 than H513 could be due to differences in P uptake. Kogbe and Adediran (2003) reported that the yield of maize varies from variety to variety.

The agronomic P use efficiency (PUE, Kg grain/Kg P) was higher in the second year and higher for the H614 maize hybrid (Fig. 1 and 2). The PUE of H513 ranged from 5.0 to 16.7 and 6.7 to 21.7 in the years 2009 and 2010, respectively. For the maize hybrid H614, the values ranged from 13 to 33.3 and 20 to 40. The addition of amendments lime, MPR and FYM had a positive effect on P use as the L+MPR+FYM had the highest PUE value.

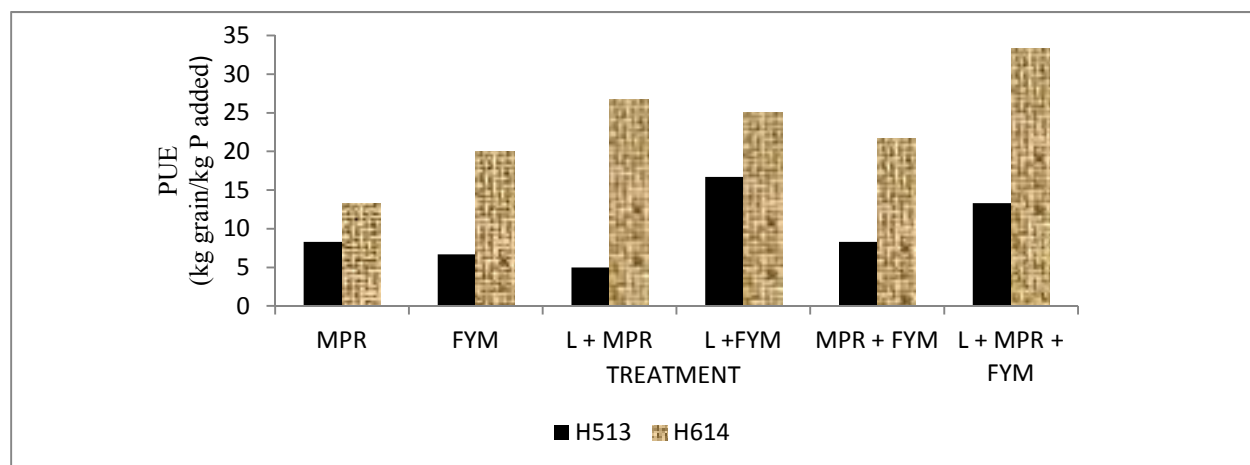


Figure 1: Phosphorus use efficiency of maize hybrids as influenced by amendments L, MPR and FYM in 2009

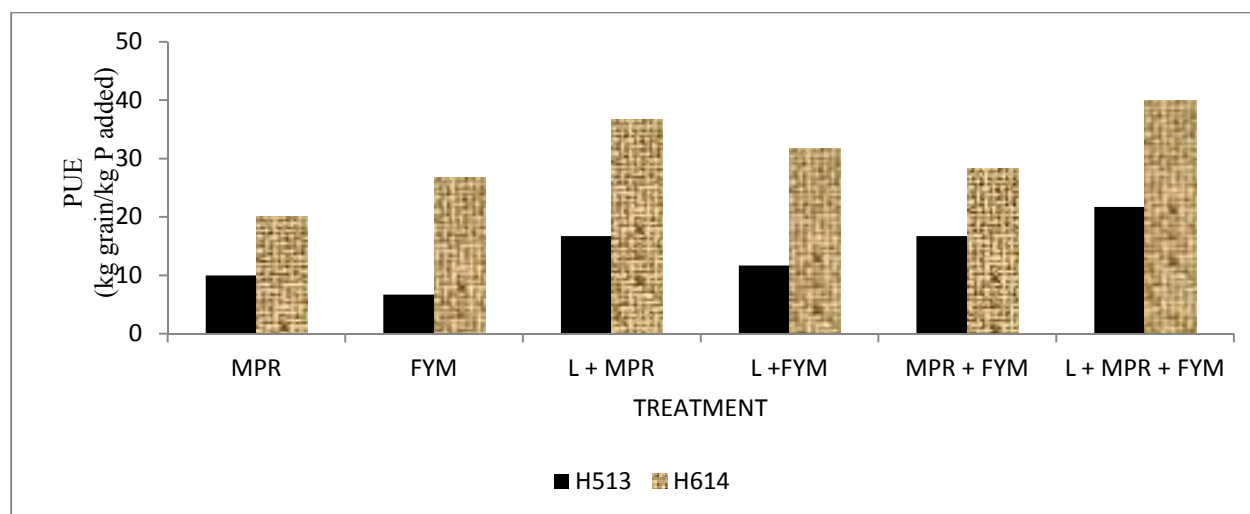


Fig 2: Phosphorus use efficiency of maize hybrids as influenced by amendments L, MPR and FYM in 2010

The higher P uptake by maize in the L+MPR+FYM treatment (Table 4) resulted to higher grain yield (Table 5) and greater PUE. Gudu et al. (2003) found that lime input raised the agronomic (external) P use efficiency of two standard maize genotypes which were susceptible to acidity. They reported negative P use efficiency for the maize genotypes in areas with high levels of Al and possible fixation of P. The latter caused negative P uptake and consequently grain yield depression. The higher PUE for H614 can also be attributed to higher uptake of P and therefore higher yields (Table 4 and 5). Kogbe and Adediran (2003) reported that PUE varied with maize hybrid and they attributed this to genetic factors.

3.4 Correlations between soil available P, P uptake, and maize yield

There were significant correlations between; soil available P and P uptake, P uptake and maize yield, and soil available P and yield across maize hybrids and years (Table 6).

Table 6. Correlations coefficients for various parameters at the maturity of maize in 2009 and 2010.

Parameter	H614		H513	
	2009	2010	2009	2010
soil available P and uptake	.616	.730*	.637	.692
P uptake and yield	.861	.944	.618	.768*
soil available P and yield	.734	.730*	.912	.768*

This indicates that contents of soil available P supplied by the amendments, influenced uptake of P and can explain the yield variations. P supply to maize by the amendments is therefore an important condition to achieve sufficient maize yields in the acid soils. Similar observations were made by Kisinyo et al. (2013).

3.5 Relative agronomic efficiency (RAE) of MPR

The RAE (%) of MPR was 50 and 66.7 for maize hybrid H513 and 61.5 and 70.6 for maize hybrid H614, in the year 2009 and 2010, respectively (Table 7).

Table 7: Relative agronomic Efficiency of MPR

Treatment	Yield (t ha ⁻¹)				Mean	
	2009		2010			
	H513	H614	H513	H614	H513	H614
C	0.9	1.9	1.1	1.7	1.0	1.8
TSP	1.3	3.2	1.7	3.4	1.5	3.3
MPR	1.1	2.7	1.5	2.9	1.3	2.8
RAE (%)	50	61.5	66.7	70.6	60.0	66.7

The values obtained indicate that MPR was as effective as TSP at equal rates of P (60 kg P ha⁻¹). The direct application of phosphate rock as P fertilizer has been found to compete favourably well with mineral fertilizers by other workers (Bolan et al., 1990; Chien et al., 1990; Akande et al., 1998; Adediran et al., 1998). The high RAE values obtained in this study can be attributed to acidity of the soil which promoted the solubilization of the MPR. The findings are in close agreement with those of Juma (unpublished data) who reported that MPR had about 70 to 75% RAE on acid soils in western Kenya. The agronomic effectiveness (capacity of P supply to crops) of PRs depends on the soil conditions (FAO, 2004). Generally in acid soils with pH below 5.0, the efficiency of PR is as high as that of acidulated phosphate (Mengel, 1986). Thuita et al. (2005) reported that the acidic soils of Siaya, Western Kenya with pH of 4.76 (H₂O) was ideal for the favorable solubilization of PRs.

Variation in RAE with the maize hybrid could be attributable to their differences in the uptake of nutrients and consequently yield. Higher grain yields were obtained in H614 maize hybrid (Table 8). The hybrid also takes up more P as discussed in section 3.2. The agronomic effectiveness of PRs depends not only on inherent factors, but also on plants/crop genotypes utilized (FAO,

2004). Akinrinde and Okeleye (1995) observed that rock phosphates had less than 50% relative agronomic efficiency (RAE) in an oxic Paleustalf especially when tomato was the test crop. They reported that crop species to be grown as well as pH of soils should be considered for efficient utilization of the sparingly soluble phosphates for both short- and long- term effects in crop production.

The higher RAE values in the second year for both maize hybrids can be attributed partly to the higher rainfall (mm) received in the second (1120) year compared to the first year (917mm). Musa et al. (2012) reported that low dissolution of sokoto rock phosphate under low rainfall conditions. The prevailing climate conditions can determine the effectiveness of rock phosphates (FAO, 2004). The residual effect of the MPR may have additionally played a role. Rowell (1994) reported that P in the MPR is available in the first season after application but remains over long periods of time hence their residual effects. This has also been reported by other workers (Skene et al., 1996; Souza and Volkweiss, 1987; Le Mare and Leon, 1989; Espinosa, 1992; Buresh et al., 1997). In terms of improving the soil P status, rock phosphates have both immediate and residual effects (FAO, 2004).

4.0 CONCLUSION

The soil amendments lime, MPR and FYM are viable alternatives to the expensive mineral P fertilizers in increasing maize productivity in the acid soils of Molo County. The amendments increased available P in soil, uptake of P, PUE and consequently maize grain yields. Their effect was greater when applied in combination. The amendments equally had a residual effect increasing the possibility to build the soil capital P. The MPR was as effective as TSP at equal rates of P (60 kg P ha^{-1}) as reflected by the RAE and can therefore be used as an affordable alternative to the more expensive water-soluble TSP fertilizer. Maize hybrids varied in RAE, P uptake, PUE and grain yield, with higher values found in H614, and is a factor of internal P requirement. The maize hybrid H513 can nonetheless be potentially recommended for adoption to especially cushion against crop failure due to the low rainfall amounts and shortened growing season brought about by a changing climate.

5.0ACKNOWLEDGEMENT

The authors gratefully acknowledge Egerton University for funding the study. We are indebted to the Kenya Agricultural Research Institute, Molo for providing the experimental fields. The Department of Crops, Horticulture and Soils-Egerton University and Department of Land Resource Management and Agricultural Technology – University of Nairobi are also acknowledged for providing the laboratory facilities.

6.0 REFERENCES

- Adediran, J.A., Oguntuyinbo, F.I., Omonode, R., Sobulo, R.A., 1998. Agronomic evaluation of Phosphorus fertilizers developed from Sokoto Rock Phosphate in Nigeria. *Comm. Soil Sci. Plant Anal.* 29: 2659-2673
- Akande, M.O., Adedira, J.A., Oluwatuyinbo, F.I. 2005. Effects of rock phosphate amended with poultry manure on soil available P and yield of maize and cowpea. *Afr. J. Biotech.* 4(5): 444-448

- 494 Akande, M.O., Aduayi, E.A., Olayinka, A., Sobulo, R.A., 1998. Efficiency of Sokoto rock phosphate as a
495 fertilizer source for maize production in South Western Nigeria. *Journal of Plant Nutrition*, 21, pp
496 1339 – 1353.
497
- 498 Akinrinde, E.A., Okeleye, K.A., 1995. Short- and long-term effects of sparingly soluble phosphates on
499 crop production in two contrasting Nigerian Alfisols. *est African Journal of Applied Ecology*. 8:
500 141-150.
501
- 502 Al-Whaibi, M.H. 1983. Mineral content of date palm varieties. *Proceedings of the first symposium on date*
503 *palm in Saudi Arabia*, March 23-25, 1983.
504
- 505 Ambrose, S.H., Sikes, N.E. 1991. Soil carbon isotope evidence for Holocene habitat in the Kenyan Rift
506 Valley. *Science*, 253 (5026): 1402-1405.
507
- 508 Anetor, M.O., Akinrinde, E.A. 2006. Response of soybean (*Glycine max* (L.) merill) to lime and
509 phosphorus fertilizer treatments on an acidi alfisol of Nigeria.
510
- 511 Baligar, V.C., Fageria, N.K., He, Z.L., 2001. Nutrient use efficiency in plants. *Commun. soil sci. plant*
512 *anal.*, 32(7&8), 921–950.
513
- 514 Baligar, V.C., Pitta, G.V.E., Gama, E.E.G., Schaffert, R.E., Bahia Filho, A.F de C., and Clark, R.B., 1997.
515 Soil acidity effects on nutrient use efficiency in exotic maize varieties. *Plant and Soil* 192: 9-13.
516
- 517 Barber S.A., Walter J.M., Vasey, E.H., 1963. Mechanisms for the movement of plant nutrients from the
518 soil and fertilizer to the plant root. *J. Agric. Food Chem.* 11, 204–207.
519
- 520 Bezzola, L.C., Lopez, S.C., Barbaro, N.O., 1994. Effectiveness of different phosphatic fertilizers measured
521 using labelled super phosphate and phosphorus taken up by plants. *Fert. Res.* 39: 31-37.
522
- 523 Bolan, N.S., White, R.E., Hedley, M.J., 1990. A review of the use of phosphate rocks as fertilizers for
524 direct application in Australia and New Zealand. *Australian Journal of Experimental Agriculture*,
525 30, pp 297-313.
526
- 527 Braschi I., Ciavatta C., Giovannini C., Gessa C., 2003 Combined effect of water and organic matter on
528 phosphorus availability in calcareous soils. *Nutr Cycl Agroecosyst* 67:67–74.
529
- 530 Bünemann, E. K., 2003 Phosphorus dynamics in a Ferralsol under maize-fallow rotations: The role of the
531 soil microbial biomass. Ph.D. dissertation. Swiss Federal Institute of Technology, Zurich,
532 Switzerland. 154 pp. <http://e-collection.ethbib.ethz.ch/show?type=diss&nr=15207>.
533
- 534 Buresh, R.J., Smithson P.C., Hellums, D.T., 1997. Building soil phosphorus capital in Africa. *In: Buresh*
535 *R.J., Sanchez P.A., Calhoun F. Replenishing Soil Fertility in Africa*, SSSA Special Publication 51,
536 111-149. Madison, WI: SSSA; ASA.
537
- 538 Chapman, R. D.; Cation exchange capacity by ammonium saturation; in: *Methods of Soil Analysis. Agron.*
539 *Part II, No.9*, edited by Black, C. A.; 891–901; Am. Soc. Agron. Madison, Wisconsin, USA; 1965.
- 540 Chien, S.H., Sale, P.W.G., Hammond, L.L., 1990. Comparison of the effectiveness of phosphorus fertilizer
541 products. In: *Phosphorus requirements for sustainable agriculture in Asia and Oceania*. *Int. Rice*
542 *Res. Inst., Manila, Philippines*, pp. 143-156.
543

- 544 Duncan, R.R., Baligar, V.C., 1990. Genetics, breeding, and physiological mechanisms of nutrient uptake
545 and use efficiency: An overview. In: Crops as Enhancers of Nutrient Use. Baligar V.C. and
546 Duncan, R.R. (Eds.), pp. 3-35. Academic Press, London.
547
- 548 Espinosa, J., 1992. Phosphorus diagnosis and recommendations in volcanic ash soils. In: *Proc. Of topsoil*
549 *phosphorus*. Decision support system workshop, College Station, TX, 11-12 Mar., p. 109-115,
550 Trop. Soils Bull. 92-01. Dept. of Agron. and Soil Sci., College of Trop. Agric. And Human
551 Resources. Univ. Hawaii, Honolulu.
552
- 553 FAO, 2004. Use of Phosphate Rocks for Sustainable Agriculture. In Fertilizer and Plant nutrition bulletin
554 13. Eds. F. Zapata and R.N. Roy. FAO, Rome, Italy.
555
- 556 Fox, T.R., Comerford, N.B., 1990. Low-molecular-weight organic acids in selected forest soils of the
557 Southeastern USA. Soil Sci. Soc. Am. J. 54: 1139-1144.
558
- 559 Furihata, T., Suzuki, M., Sakurai, H., 1992. Kinetic characterization of two phosphate uptake systems
560 with different affinities in suspension-cultured *Catharanthus roseus* protoplasts. Plant Cell Physiol
561 33: 1151-1157.
562
- 563 Geelhoed J. S., van Riemsdijk W. H., Findenegg G. R., 1999. Simulation of the effect of citrate exudation
564 from roots on the plant availability of phosphate adsorbed on goethite. Eur J Soil Sci 50:379-390.
565
- 566 Ginkel van, C.E., 2011. Eutrophication: Present reality and future challenges for South Africa . Presented
567 Vol 37, No 5 : 693-702.
568
- 569 Gudu, S.O., Okalebo J.R., Othieno, Obura, P.A., Ligeyo, D.O., Shulze, D., Johnston, C. 2005. Response of
570 five maize genotypes to nitrogen, phosphorus and lime on acid soils of Western Kenya. African
571 Crop Science Conference Proceedings, Vol. 7. pp. 1109-1115.
572
- 573 Haynes, J.R. 1982. Effects of liming on P availability in acid soils. Plant and Soil 68 (3): 289-308.
- 574 Holford, I.C.R., 1997. Soil phosphorus: its measurement and its uptake by plants. Australian Journal of
575 Soil Research 35: 227-239.
576
- 577 Horst, W.J., Abdou, M., and Wiesler, F.1993. Genotypic differences in phosphorus efficiency of wheat. In:
578 Plant nutrition – from genetic engineering to field practice. Proceedings of the Twelfth
579 International Plant Nutrition Colloquium, Barrow, N.J. (Ed.), pp. 367-370. Kluwer, Amsterdam.
580
- 581 Hue, H., Tan, C., Cai, C., He, J., Li, X., 2001. Availability and residual effects of phosphate rocks and
582 inorganic P fractionation in a red soil of central China. Nut Cycl. Agroecosyst. 59: 251-258.
583
- 584 Hue, N.V., Gaddock G.R, Adams, F. 1986. Effect of organic acids on Al toxicity in subsoils. Soil Sci.
585 Soc. Am. J. 50: 28-34.
586
- 587 Jaetzold, R., Schimdt, H., Hornetz, B. and Shisnaya, C. 2007. Farm Management Handbook of Kenya.
588 Natural Conditions and Farm Mannegement Information. Volume IIA. Nairobi Kenya. 319 pp.
589
- 590 Jugenheimer, R.J. 1985. Corn - improvement, seed production, and uses. Robert E. Krieger Publishing Co.,
591 Malabar, FL.
592

- 593 Kingston, J.A., Deino, A.L., Edgar, R.K., Hill, A., 2007. Astronomically forced climate change in the
594 Kenyan Rift Valley 2.7-2.55 Ma: implications for the evolution of early hominin ecosystems. *J. Of*
595 *Hum. Nutr.* 53(5):487-503.
- 596
- 597 Kisinyo, P.O., Othieno, C.O., Okalebo, J.R., Kipsat, M.J., Serem, A.K. and Obiero, D.O. 2005. Effects of
598 lime and phosphorus application on early growth of *Leucaena* in acid soils. *Crop Science*
599 *Conference Proceedings*, Vol. 7. pp. 1233-1236.
- 600
- 601 Kisinyo P. O., Othieno, C. O., Gudu S. O. Okalebo, J.R., Opala, P. A., , Maghanga, J. K., Ng'etich, W. K.,
602 Agalo, J. J., Opile, R. W., Kisinyo, J. A., Ogola, B. O., 2013. Phosphorus Sorption and Lime
603 Requirements of Maize Growing Acid Soils of Kenya. *Sustainable Agriculture Research*; Vol. 2,
604 No. 2. Published by Canadian Center of Science and Education.
- 605
- 606 Kogbe, J.O.S., Adediran, J.A. 2003. Influence of nitrogen phosphorus and potassium application in the
607 yield of maize in the savanna zone of Nigeria. *African J. Biotech.* 2 (10): 345-349.
- 608
- 609 Kolawole, G. O., Tian, G., 2007. Phosphorus fractionation and crop performance on an alfisol amended
610 with phosphate rock combined with or without plant residues. *African Journal of Biotechnology*
611 6(16): 1972-1978.
- 612
- 613 Landon, J.R., 1991. *Booker Tropical Soil Manual. A Handbook for soil survey and agricultural land*
614 *evaluation in the tropics and subtropics.* Longman Scientific and Technical Essex, New York.
615 474p.
- 616
- 617 Le Mare, P.H., Leon, A., 1989. The effect of lime on adsorption and desorption of phosphates in five
618 Colombian soils, *Journal of Soil Science*, 40: 59-69.
- 619
- 620 Lelei, J.J., Onwonga, R.N. and Mochoge, B.O. 2006. Interactive effects of lime, manure, N and P
621 fertilizers on maize (*Zea mays* L.) yield and N and P uptake in an acid mollic Andosol of Molo
622 Kenya. *Egerton Journal: Science and Technology series. Volume VI. No. 1.* pp 141-156.
- 623
- 624 Machado, C.T. Almeida, D.L., and Machado, A.T. 1999. Variability among maize varieties to phosphorus
625 use efficiency. *Bragantia* 58(1): 109-124.
- 626
- 627 Marschner, H., 1986. *Mineral Nutrition of Higher Plants.* Academic Press, London. 674 pp.
- 628
- 629 Mathur, B.S., Suresh, L., 1989. Effect graded levels of rock phosphate on plant nutrition of an Alfisol. *J. of*
630 *Indian Soc. of Soil Sci.* 37: 815-857.
- 631
- 632 Mati, B.M., 2000. The influence of climate change on maize production in the semi-humid-semi-arid areas
633 of Kenya. *J. of Arid Environ.* 46 (4): 333-334.
- 634
- 635 McLean, E.; 1965. Aluminum; in: *Methods of Soil Analysis. Agron. No. 9. Part II*, edited by Black, C. A.;
636 978-998; Am. Soc. Agron, Madison, Wisconsin, USA.
- 637
- 638 Mengel, K., 1986. Umsatz im Boden und Ertragswirkung rohphosphathaltiger Düngemittel. *Z.*
639 *Pflanzenmähr. Bodenk.* 149, 674-690.
- 640
- 641 Mokwunye, A.U., de Jager, A., Smaling, E.M.A., 1996. Restoring and Maintaining the Productivity of
642 West African Soils, Keys to Sustainable Development. *Miscellaneous Fertilizer Studies No. 14.*
643 IFDC, Africa, Lome, Togo.

- Motavali, P.P., 1994. Perception management of farm yard manure in the semi-arid tropics of India. *Agricultural systems* 46 (2): 189-204.
- Musa, I.M., Singh, A., Abubakar, L., Noma, S.S., Alhassan, J., Haliru, B.S., 2012. Influence of Cultivar and Sokoto Phosphate Rock Levels on the Yield and Yield Components of Groundnut (*Arachis hypogaea* L.) in Dry Sub-Humid Sokoto Area, Nigeria . *Nigerian J. of Basic and Applied Science* (20(1): 49-54.
- Myint, A.K., Yamakawa. T., Kajihara Y., Zenmyo, T., 2010. Application Of Organic and Mineralised Fertilisers On Growth, Yield And Nutrient Accumulation Of Rice. *Science World Journal* Vol 5 (No 2) 2010.
- Ndung'u, K.W., Okalebo, J.R., Othieno, C.O., Kifuko, M.N., Kipkoech, A.K. Kimenye, L.N., 2006. Residual effectiveness of Minjingu phosphate rock and improved fallows on crop yield and financial returns in western Kenya. *Experimental Agriculture* 42:323-336.
- Negassa, W., Gebrekidan, H., Friesen, D. K. 2005. Integrated Use of Farmyard Manure and NP fertilizers for Maize on Farmers' Fields. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 106: 131–141.
- Nekesa, A. O., Okalebo, J.R., Othieno, C.O., Thuita, M. N., Kipsat, M., Bationo, A., Sanginga, N., Kimettu, J., Vanlauwe, B., 2005. The potential of Minjingu phosphate rock from Tanzania as a liming material: Effect on maize and bean intercrop on acid soils of western Kenya *African Crop Science Conference Proceedings*, Vol. 7. pp. 1121-1128.
- Nielsen, N.E., Barber, S.A., 1978. Differences between varieties of corn in kinetics of phosphorus uptake. *Agronomy Journal* 70(5): 695-698.
- Nyandat, N.N., 1981. The primary minerals in some Kenya's topsoils and their significance to inherent soil fertility. *East African Agricultural and Forestry Journal* 46 (3): 71- 76.
- Oberson, A., Fardeau, J.C., Besson, J.M., Sticher, H., 1993. Soil phosphorus dynamics in cropping systems according to conventional and biological agricultural soils. *Biol Fert Soils* 16, 111–117.
- Odiambo, J.O. 1989. The effect of nitrogen fertilization in maize (*Zea mays* L. *Katamani composite* B.) performance and nitrogen mineralization in Kabete Nitisols. Msc. Thesis, University of Nairobi, Kenya.
- Okalebo, J.R., Gathua, K.W., Woomer, P.L., 2002. Laboratory methods of plant and soil analysis: a working manual, 2nd edn. TSBF-UNESCO, Nairobi.
- Okalebo, J.R., Otieno, C.O., Woomer, P.L., Karanja, N.K., Semoka, J.R.M., Bekunda, M.A., Mugendi, D.N., Muasya, R.M., Bationo, A., Mukhwana, E.J., 2006. Available technologies to replenish soil fertility in East Africa. *Nutrient Cyc. in Agroecosyst.* 76: 153-170.
- Onwonga, R.N., Lelei, J.J., Freyer, B., Friedel, J.K., Mwonga, S.M. Wandahwa, P., 2008. Low cost techniques for enhancing N and P availability and maize (*Zea mays* L.) performance on acid soils. *World Journal of Agricultural Sciences* 4 (S): 862-873.

- 694 Opalla, P.A., Okalebo, J.R., Othieno, Caleb., 2013. Comparison of effects of phosphorus sources on soil
695 acidity, available phosphorus and maize yields at two sites in western Kenya. Archives of
696 Agronomy and Soil Science, 59 (3): 327-339.
697
- 698 Patz, J.A., Campbell-Tendrum, D., Holloway, T., Foley, J.A., 2005. Impact of regional climate change on
699 human health. Nature 438: 310-317.
700
- 701 Peterburgski A.V.,1986. Practical Guidance on Agro-chemistry. Kolos Publ., Moscow.
702
- 703 Rowell, D.L., 1994. Soil science: methods and applications. Longman scientific and Technical. 350 pp.
704
- 705 Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science 295: 2019-2020.
706
- 707 Sanchez, P.A., Uehara, G., 1980. Management consideration acid soils with high phosphorus fixation
708 capacity. In, Khasawneh F.E., Sample E.C. and Kamprath E.J. (Eds), The Role of Phosphorus in
709 Agriculture. ASA, CSA, and SSSA, Madison, WI, 471–514.
710
- 711 Sholly D. M., Richert B. T., Sutton A. L., Joern B. C., 2010 Effects of nitrogen and phosphorus application
712 from swine manure on winter wheat growth and nutrient utilization. Com Soil Sci Plant Ana
713 41:1797–1815.
714
- 715 Skene, K.R., Kierans, M., Sprent, J.I., Raven, J.A. 1996. Structural aspects of cluster root development and
716 their possible significance for nutrient acquisition in *Grevillea robusta* (Proteaceae). Annals of
717 Botany 77, 443–451.
718
- 719 Sokora, F.J.,2002. Evaluating and quantifying the liming potential of phosphate rocks. Nutr Ccl
720 Agroecosyst. 66: 59-67.
721
- 722 Souza, D.M.G. de; Volkweiss, S.J., 1987. Rendimento da matéria seca e conteúdo de fósforo da parte
723 aérea do milho influenciados pela adubação com superfosfato triplo em pó e em grânulos. Rev.
724 Bras. Ci. Solo 11: 127-132.
725
- 726 SPSS., 1999. Statistical package of the social sciences vol. 10.0. SPSS Inc., Chicago, Illinois.
727
- 728 Staunton S, Leprince, F., 1996. Effect of pH and some organic anions on the solubility of soil phosphate:
729 implications for P bioavailability. European J. Soil Sci., 47(2): 231-239.
730
- 731 Szilas, C., Semoka, J. M. R., Borggaard, O. K., 2007. Can local Minjingu phosphate rock replace
732 superphosphate on acid soils in Tanzania? Nutrient Cycling in Agroecosystems 77 (3): 257-268.
733
- 734 Tossah, B.K., 2000. Influence of soil properties and organic inputs on phosphorus cycling in herbaceous
735 legume-based cropping systems in the West African derived savanna. PhD. Thesis, Katholieke
736 Universiteit, Leuven, Belgium.
737
- 738
- 739 Thuita, M.N., Okalebo, J.R., Othieno, C.O., Kipsat, M.J., Batiano, A., Sanginga, N., Vanlauwe, B., 2005.
740 An attempt to enhance solubility and availability of phosphorus from phosphate rocks through
741 incorporation of organics in western Kenya. African Crop Science Conference Proceedings, Vol.
742 7. pp. 1021-1027.

- 743
- 744 Ullrich-Eberius C, Novacky A, van Bel A., 1984. Phosphate uptake in *Lemna gibba* G1: energetics and
745 kinetics. *Planta* 161: 46–52.
- 746
- 747 Uzoho, B U., Oti, N.N., 2005. Phosphorus adsorption characteristics of selected southeastern nigerian
748 soils. *Agro-Science* Vol. 4 (1): 50-55.
- 749
- 750 Valluru A., Vadez V., Hash C. T., Karanam P., 2010 A minute P application contributes to a better
751 establishment of pearl millet (*Pennisetum glaucum* (L.) R. Br.) seedling in P deficient soils. *Soil*
752 *Use Manag* 26:36–43.
- 753
- 754 Van der Eijk, 1997. Phosphate Fixation in Kenyan Soils. PhD Thesis, Wageningen Agricultural
755 University, Wageningen, The Netherlands. 162 pp.
- 756
- 757 Venek, V. 2003. Farm yard manure application on root crops for higher yields. *Plant Soil Environ.* 49:
758 197-202.
- 759
- 760 Violante A., Gianfreda L., 1993 Competition in adsorption between phosphate and oxalate on an
761 aluminum hydroxide montmorillonite complex. *Soil Sci Soc Am J* 57:1235–1241.
- 762
- 763 Walkley, A. and Black, C. A., 1934. An examination of the Degtjareff method for deter- mining soil
764 organic matter and a proposed modification of the chromic acid titration method; *Soil Sci.*; 37:29–
765 38.
- 766
- 767 Wasonga, C.J., Sigunga1, D.O., Musandu, A.O. 2008. phosphorus requirements by maize varieties in
768 different soil types of western kenya. *african crop science journal*, vol. 16, no. 2, pp. 161 – 173.
- 769
- 770 Wuta M ., Nyamugafata., P. 2012. Management of cattle and goat manure in Wedza smallholder farming
771 area, Zimbabwe. *African Journal of Agricultural Research* Vol. 7(26), pp. 3853-3859.
- 772
- 773 Zafar, M., Abbasi, K., Khaliq, A., Rehman, Z., 2011. Effect of combining organic materials with inorganic
774 phosphorus sources on growth, yield, energy content and phosphorus uptake in maize at
775 Rawalakot Azad Jammu and Kashmir, *Pakistan Archives of Applied Science Research*, 3 (2): 199-
776 212.
- 777