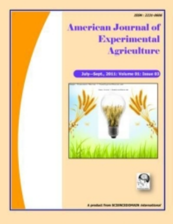

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Comparative Effects of Soil Amendments on Phosphorus Use and Agronomic Efficiencies of Two Maize Hybrids in Acidic Soils of Molo County, Kenya

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Authors' contributions

The authors jointly designed the study and wrote the protocol. Authors RNO and JJL performed the statistical analysis and wrote the first draft of the manuscript. Authors JJL and JKM managed the analyses of the study. Authors RNO and JJL managed the literature searches and addressed subsequent reviewer comments and suggestions for improvement. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

The deficiency of P and the shortened growing seasons 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, Kenya. The current study therefore 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 2^3 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, FYM+MPR and L+FYM+MPR. The relative

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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 hybrid H513 and H614 were the test crops in both experiments and constituted the main plots. The split plots were control (0 kg P ha^{-1}), triple super phosphate (60 kg P ha^{-1}) and MPR (60 kg P ha^{-1}). Soil available P and its uptake, PUE, RAE and maize yields were the parameters 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+FYM+MPR treatment and for 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 for the maize hybrid H614. The combined application of soil amendments could thus 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. Moreover, it has a low P requirement and a short growth cycle thus making it an ideal variety, economically, for smallholder farmers.

Keywords: Climate change; farm yard manure; maize hybrids; Minjingu phosphate rock; soil acidity.

1. 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 [1,2]. The deficiency is largely due to low occurrence of P-containing minerals [3,4], P-fixation in acid soils [5] and continuous cropping without commensurate nutrient replenishment [6,7,1].

In high P fixing soils, such as the case for Molo County in Kenya, the application of large amounts of inorganic fertilizer can quench the soils' P sorption capacity and avail the excess P in soil [8]. The use of high fertilizer amounts is, however, impractical for the impoverished smallholder farmers in the area [2]. The application of mineral fertilizers has also been reported to have negative environmental consequences such as nutrient immobilization and ground water pollution [9,10]. To improve productivity of the acid soils, rebuilding soil P fertility in a feasible and environmentally friendly manner is thus imperative. This can be achieved by the application of soil amendments such as phosphate rocks (PRs), lime and manures [11].

Minjingu Phosphate Rock (MPR) is the predominant type of PR deposit in Eastern Africa with sufficient quantity and reactivity cum potential for direct application [12]. The direct application of phosphate rock supplies P, and reduces dependency on expensive imported fertilizers [11,12]. Increased yields have been reported where MPR has been used as a source of P to crops [13,14]. Lime, on the other hand, reduces the activity of Al ions resulting in increased extractable P [15,16]. Kisinyo et al. [17] and Gudu et al. [18] 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 [19] and the organic acids produced in the process chelate P-fixing elements in the rhizosphere or decomposition system [20].

Opalla et al. [21] 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 [22,23]. One of the evidences observed in Molo County is reduced rainfall leading to shortened growing seasons [24,25]. 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 [22]. 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. MATERIAL 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) located in Molo County, Kenya. The County is categorized in the medium to high potential agro ecological zone of Kenya [26]. The mean annual rainfall is 1171 mm [26]. 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 correspondingly 917mm and 1120 mm. The mean maximum and minimum air temperatures were 20.6°C and 6.9°C, respectively. The soils are well drained, deep, dark reddish brown with a mollic A horizon and are classified as Mollic Andosols [26]. The initial physical and chemical properties of the soils (Table 1) were acidic with low available P and nitrogen contents. The total exchangeable bases and CEC were rated as medium [27].

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
Kcmol$_c$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

Two similar experiments involving hybrid maize H614 and H513 respectively, as the test crops, were 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 maize hybrids. The experiments were laid out in randomized complete block design with a 2^3 factorial arrangement. 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, FYM+MPR, and L+ FYM+MPR. The treatments were similarly applied to the two maize hybrids, H513 and H614, planted in the 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 control (0 kg P ha^{-1}), triple super phosphate (60 kg P ha^{-1}) and MPR (60 kg P ha^{-1}).

2.3 Agronomic Practices

Land was prepared manually using hand hoes. Lime as $CaCO_3$ (40% Ca) and MPR were broadcasted and incorporated in soil to depth of 15 cm two weeks prior to planting, as the moisture content was high, using hand hoes. 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 normally limiting nitrogen (N) nutrient, Calcium Ammonium Nitrate (CAN) fertilizer was applied to all treatments as a top dress one month after planting, at the rate of 60 kg ha^{-1}. The maize hybrids; H614 and H513, were sown at the rate of two seeds per hill on plots measuring 3.75 cm x 4.8 cm. The maize was planted in the long rain season of 2009 and 2010 at a 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 [28].

2.4 Sampling of Soils, Plants and Farmyard Manure

2.4.1 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.

2.4.2 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 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^{o} C for 72 hours. The weights of the oven dry sub-samples were recorded and used to calculate the total above-ground dry matter yields.

2.4.3 Farm Yard Manure

Approximately 1 kg of 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. It was 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: H_20 and KCl: 1:2.5), texture (hydrometer method), total N (Kjedahl method) total carbon [29], Exchangeable Al [30], CEC [31], mineral N and available P according to Okalebo et al. [32]. Exchangeable bases (K, Ca and Mg) were extracted with 1.0 M-ammonium acetate at pH 7 and measured by atomic adsorption spectrophotometer (©Analytic jena). Plant samples were ground and passed through 2 mm sieve and their P content analyzed according to Okalebo et al. [32] 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. [32].

2.6 Calculation Procedures and Statistical Analysis

The nutrient uptake, grain yield, phosphorus use efficiency and relative agronomic efficiency were calculated as follows;

Total Nutrient uptake*:* The total nutrient uptake was calculated at the three maize growth stages using the following formulae [33];

Total nutrient uptake = nutrient concentration x dry matter yield ……..………………. (1)

Maize grain yield*:* In the determination of maize grain yield, plants from three middle rows of each plot were 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;

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

The agronomic P use efficiency (PUE)*:* 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) according to Fageria et al. [34]:

PUE = (Yp-Yc)/Pw ……………………………………………………………........……… (3)

Relative agronomic efficiency (RAE)*:* 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}) according to Chien et al. [35].

RAE = [(yMPR – ycontrol / yTSP – ycontrol) × 100] %, ……………....…….….……….…… (4)

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

2.7 Statistical Analysis

Analysis of variance (ANOVA) using a general linear model [36] was 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 using Spearman's correlation coefficient by comparing their means.

3. RESULTS AND DISCUSSION

3.1 Chemical Composition of Farmyard Manure

The farm yard manure (FYM) applied, initially stored under shade, a good management practice, 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 [37] and could potentially improve soil productivity and fertility and consequently the yield of crops [38].

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 [39].

Table 2. Chemical composition and nutrient quantity (kg) in 5tha^{-1} of FYM

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

3.2 Soil Available P at Different Stages of Plant Growth

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

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
FYM+RP	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+FYM+RP	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

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

Means in a column followed by the same letter are not significantly different ($P<0.05$) according to Turkey mean separation procedure

In the year 2009, 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 levels of soil available P followed the order; L+FYM+MPR > FYM+MPR > L+MPR> L+FYM (Table 3). For the maize hybrid H513, significantly higher soil available P was found in the L+FYM+MPR treatment at the seedling stage of maize growth. During maize tasseling, for both H614 and H513, the combined treatments, L+FYM+MPR, FYM+MPR and L+MPR, had significantly higher amounts of P. At the physiological maturity of maize the available P in soil was significantly higher in the L+FYM+MPR treatment for both maize hybrids (Table 3).

In the second year, significantly higher amounts of soil available P (ppm) were obtained in the L+FYM+MPR 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+FYM+MPR and FYM+MPR treatments at seedling stage of maize growth (Table 3). At the tasseling stage, L+FYM+MPR, FYM+MPR and L+MPR treatments 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+FYM+MPR treatments for both H513 and H614, respectively.

A paired sample *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 progression of plant growth can partly be attributed to crop uptake which is continuous throughout crop growth. Maize draws most nutrients from the soil from about 10 days before tasseling to about 25-30 days after tasseling [40,41]. P Adsorption, precipitation and lack of application of the soil acidity ameliorating amendments could also have been responsible for the declining available P levels in the control treatment (Table 3) with low pH level (soil pH (H_20) < 4.7). Mokwunye et al. [42] reported that P deficiency observed in acid soils is often associated with high P fixation and P uptake rates are highest between pH 5.0 and 6.0 where $H_2PO_4^-$ dominates [44,45]. Holford [43] points out that more than 80% of the applied P in agricultural systems undergoes adsorption, precipitation, or conversion to the organic form. The conversion of P from inorganic into the organic forms by microbes may have also contributed to declining P levels in the ameliorated soil. Soil microbes release immobile forms of P to the soil solution and are also responsible for the immobilization of P [43].

The higher levels of P in the treatments containing the amendments L, MPR and FYM than in the control could be attributed to increased soil pH and P desorption following lime and MPR application. FYM also increases available P in soil through chelation and decomposition [46]. 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 [47,48,49] have reported competition between low-molecular-weight organic acids and phosphates for sorption sites that usually favours adsorption of organic acids and delays P adsorption.

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 lime, FYM and MPR. According to Rowell [50], the rapid adsorption of P onto 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. [39] 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+FYM+MPR, FYM+MPR, 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+FYM+MPR, 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 and this is corroborated by several authors [51, 52, 53] who reported that plant readily available, labile and moderately labile P fractions were improved when PR was applied in combination with plant residues.

3.3 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 treatments and maize hybrids (Table 4). The uptake was higher in the treatments where amendments L, MPR and FYM had been applied than the control.

The P uptake (mgg^{-1}) in 2009 was significantly higher in the L+FYM+MPR and FYM+MPR treatments for maize hybrid H614 at seedling (Table 4). At the tasseling stage, it was higher in the L+FYM+MPR treatments. At maturity there were no significant differences in P uptake in all treatments except for the control which had the least P uptake (Table 4). Significantly higher amounts of P were registered in the L+FYM+MPR 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+FYM+MPR, L+MPR and L+FYM (Table 4). 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+FYM+MPR treatment had significantly higher uptake of P (Table 4) for the maize hybrid H513, at seedling stage of maize growth for both years. At tasseling stage, all the combined treatment (L+FYM+MPR, FYM+MPR, L+MPR, L+FYM) application recorded significantly higher P uptake in both years. At the maturity of maize for both years, the control had significantly lower P uptake (Table 4).

Table 4. Means of plant P uptake (mgg-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	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
FYM+RP	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+ FYM+RP	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

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

Means in a column followed by the same letter are not significantly different (P<0.05) according to paired t –tests

P uptake was higher in hybrid maize 614 when compared to that of H513 at the physiological maturity of the grain of maize A paired sample t test showed that the differences in P uptake by the two maize hybrids were statistically significant (*t* (7) = 7.0, *p* = .00, α = .05) in the second year (2010). The observed increase in plant P uptake by maize from the seedling to the tasseling growth stage was due to plant uptake which is continuous throughout the growth of the plant.

The observed variations in P uptake across soil amendments can be attributed to the differences in soil available P in the different treatments. The control treatment had lower available P content due to fixation in the acid soil. Wasonga et al. [54] observed that, sites with unfavourable soil conditions like the high Al saturation, the key fixer of P in acid soils is Al ion [55], resulted in relatively low P uptake. The increase in pH after application of lime and MPR (results not shown) may have led to desorption of P and thus increased the soil available P. Haynes [56] reported that the adsorption of phosphate generally decreases as the pH is raised by liming. Anetor and Akinrinde [57] reported improved available P content in acid soils of Ikenne, Nigeria due to the release of P from sorption sites by lime reaction. The amendments, MPR or FYM, also supplied P. The higher amounts of soil available P in the 2010 season is attributable to the residual effects of the amendments lime, FYM and MPR.

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. According to Marschner [58] and Negassa et al. [39], FYM contains other nutrients such as N and S and improves soil physical properties. Uzoho and Oti [59] reported that the efficient utilization of P depends also on the availability of other nutrients in addition to a good rooting medium.

The low uptake of P by maize hybrid H513 compared to H614 can be attributed to its lower biomass as the P uptake is a product of biomass and P content. Maize hybrid H513 has a shorter growing cycle and produced lower biomass and therefore had lower P uptake compared to the longer maturing hybrid maize H614. Maize varieties are known to vary in P uptake and utilization efficiencies [60, 61, 62, 63]. Genetic and physiological components of plants have pro-found effects on their abilities to absorb and utilize nutrients under various environmental and ecological conditions [64]. Wasonga et al. [54] also observed differences in P requirements by open pollinated maize varieties and hybrids.

3.4 Grain Yields and Agronomic Phosphorus Use Efficiencies of the Maize Hybrid

Maize grain yields were significantly greater in the second year across treatments and maize hybrids with maize hybrid H614 registering higher yields than H513 (Table 5). Comparing treatments and years (Table 5), the grain yield for maize hybrid H614 was highest in treatment L+FYM+MPR in 2009 and, L+FYM+MPR and L+MPR in 2010. In 2009, the grain yield for maize hybrid H513 was significantly higher in L+FYM+MPR and L+MPR treatments while in 2010, it was high in the L+FYM+MPR treatments. The increases in grain yield over the control were pronounced for the combined amendments and generally higher for maize hybrid H614 compared to H513 (Table 5).

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

Treatment	2009				2010			
	H513	H614	%IOC H513	%IOC H614	H513	H614	%IOC H513	%IOC 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
FYM+MPR	1.7^{b}	3.2^{c}	88.9	68.4	2.1^{b}	3.4^{bc}	90.9	100.0
L+FYM+MPR	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; RP = MPR
Means in a column followed by the same letter are not significantly different (P<0.05) according to paired t –tests

The higher grain yields in the second year were partly as a result of the elevated available P content in soil due to residual effect of the amendments FYM and MPR [65] and its subsequent uptake by maize. The lower maize yields in the control may be attributed to the low availability of P due to fixation in the acid soil. Conversely, the supply of P by the amendments applied singly or in combination contributed to the maize grain yield increases. Wasonga et al. [54] 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. Sholly et al. [66] recorded about 29% yield increase with manure application in wheat. Application of 60 kg P ha^{-1} as MPR has also been found to significantly increase bean yields by over 260 % above the control [67]. They [67] 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. [68] 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 higher P uptake attributed to the longer growing cycle and variety differences There was also a stronger correlation between P uptake and yield for hybrid maize H614 than H513 (Table 6). Kogbe and Adediran [69] reported that the yield of maize varies from variety to variety.

Agronomic P use efficiency (PUE): The agronomic P use efficiency (PUE, Kg grain Kg P^{-1}) was pronounced in the second year and was high for the maize hybrid H614 (Fig. 1 and 2). The addition of amendments; lime, MPR and FYM had a positive effect on P use as the highest PUE value registered in the L+FYM+MPR treatment.

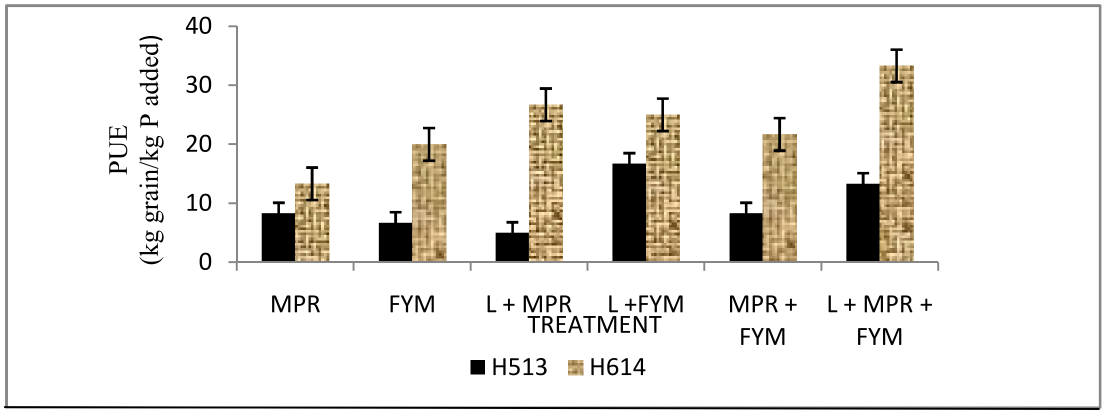

Fig. 1. Phosphorus use efficiency of maize hybrids as influenced by amendments L, MPR and FYM in 2009

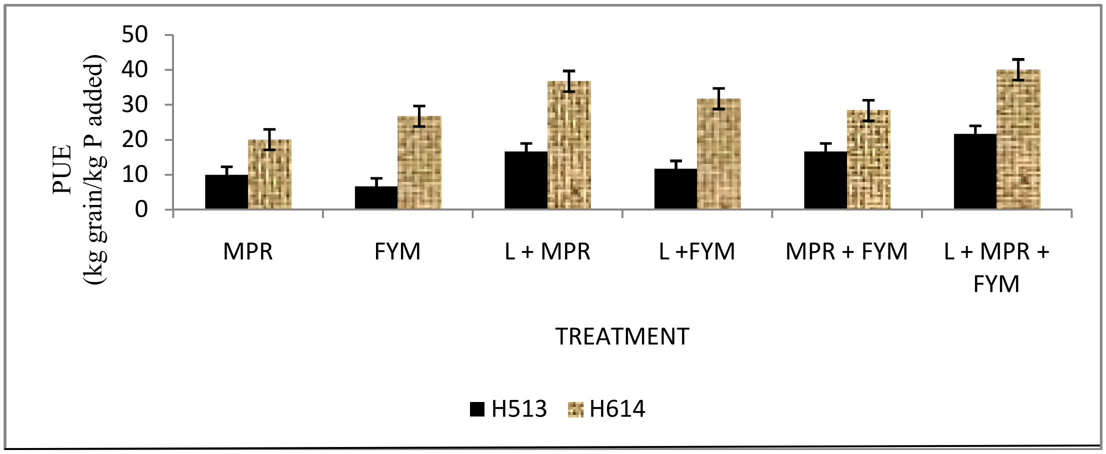

Fig. 2. Phosphorus use efficiency of maize hybrids as influenced by amendments L, MPR and FYM in 2010

The higher P uptake by maize following application of L+FYM+MPR treatment (Table 4) may have resulted to the higher grain yield (Table 5) and greater PUE. Gudu et al. [18] 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 maize hybrid H614 can also be attributed to better uptake of P and thus higher yields (Table 4 and 5). Kogbe and Adediran [69] reported that PUE varied with maize hybrid and they attributed this to genetic factors.

3.5 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. Correlation coefficients for various parameters at maize maturity 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*

The significant correlations for the various parameters measured (Table 6) indicates that the amounts of soil available P supplied by the amendments, influenced P uptake and could explain the yield variations. P supply to maize by the amendments is consequently an important condition to achieve sufficient maize yields in the acid soils. Similar observations were made by Kisinyo et al. [70] while studying phosphorus sorption and lime requirements of maize growing on acid soils of Kenya

3.6 Relative Agronomic Efficiency (RAE) of Minjingu Phosphate Rock

The RAE values of MPR for the maize hybrid H513 and H614 in the two cropping years imply that, at equal rates of P (60 kg P ha^{-1}), MPR was as effective as TSP (Table 7).

Table 7. Maize hybrid yields and relative agronomic efficiency of MPR

Treatment	**Yield (t ha^{-1})**					
	2009		**2010**		**Mean**	
	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 direct application of phosphate rock as P fertilizer has been found to compete favourably well with mineral fertilizers by other workers [71,35,72,51]. 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 [1]. Generally in acid soils with pH below 5.0, the efficiency of PR is as high as that of acidulated phosphate [73]. Thuita et al. [74] reported that the acidic soils of Siaya, Western Kenya with pH of 4.76 (H_2O) was ideal for the favorable solubilization of PRs.

Variation in RAE across maize hybrids could be attributed to their differences in P uptake and consequently yield. The hybrid H614 takes up more P, partly due to its longer growth cycle, and as a result its grain yields were greater than for the maize hybrid H513 (Table 7). The agronomic effectiveness of PRs depends not only on inherent factors, but also on plants/crop genotypes utilized [1]. Akinrinde and Okeleye [75] 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 received in the second (1120 mm) year compared to the first year (917mm). Musa et al. [76] reported low dissolution of sokoto rock phosphate under low rainfall conditions. The prevailing climate conditions can determine the effectivess of rock phosphates [1]. The residual effect of the MPR may have additionally played a role. Rowell [50] 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 [76,77,78,79,80]. In terms of improving the soil P status, rock phosphates have both immediate and residual effects [1].

4. 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 thereby 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 maize hybrid H614. 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. Moreover, the maize hybrid has a low P requirement and a short growth cycle, thus making it an ideal variety for smallholders economically.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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