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Effect of Phosphate Levels on Soil Rhizosphere Nutrient Balances and Finger Millet Yield

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Authors' contributions

This work was carried out in collaboration between all authors. Author WNW designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors WNW and JPGO reviewed the study design and all drafts of the manuscript. Authors NKK and HFO managed the analyses of the study and performed the statistical analysis. Author WNW managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Soil infertility is one of the main factors leading to low finger millet production in the semi-arid tropics of Kenya. About 50-80% of P applied as fertilizer is adsorbed by soil and the amount of P needed to achieve maintenance of its adequate status and influence on other soil properties has not been well documented. An on-station experiment was therefore conducted at the KALRO-Kiboko research station during the 2014 long and 2015 short rain seasons to investigate the influence of phosphorus rates on soil rhizosphere chemical properties and yield of three finger millet varieties. The experiment was laid out in a Randomized Complete Block Design in factorial arrangement and replicated three times. There were four P levels (0, 12.5, 25 and 37.5 kg ha^{-1} P_2O_5) and three varieties (U15, P-224 and local check-Kat FM1). Phosphorus application reduced

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the soil pH significantly for both seasons with the 37.5 kg ha^{-1} P_2O_5 rate eliciting the greatest pH from 9.26 to 7.90 (1.36 units) during the long rain season. As expected, soil phosphorus increased with the highest rate with 11 ppm during the long rain season and 9 ppm for the short rains. The organic carbon increased by 0.28% for the long rain season on the 25 kg ha^{-1} P_2O_5 rate while the highest rate increased total N by 0.05%. The 25 kg ha^{-1} P_2O_5 rate and U-15 indicated the highest yield for both seasons with a maximum of 3.71 t ha^{-1} realized during the short rain season. Monitoring change in soil nutrient status is important for prescribing P fertilization in order to maintain or replenish soil fertility. The application rate of 25 kg ha^{-1} P_2O_5 led to the optimal yields under the improved variety and hence the study recommends this rate.

Keywords: Finger millet; soil infertility; phosphorus; adsorbed; rhizosphere.

1. INTRODUCTION

Finger millet *(Eleusine coracana)* is an important staple cereal food crop for millions of people in the semi-arid regions of the world, particularly in the sub-Saharan Africa and especially among the smallholder farmers. It remains highly valued by traditional farmers because it is nutritious, drought tolerant and its propagation may help to mitigate climate change. The annual production of the crop in the world is 4.5 million metric tonnes whereby 2 million is produced in Africa [1]. Kenya produces an average of between 0.5-0.75 t ha^{-1} which is just about 15-16% of the theoretical maximum [2]. With the persistently widespread declining crop yields, there is great fear that one day the world will be in trouble as food production may not be enough to meet the demand of the fast growing human population which is projected to be 8,000 million by 2020 and 9,400 million by 2050 [3]. Decline in crop yields is mainly caused by loss of soil fertility from nutrient deficiencies caused by factors such as erosions, nutrient imbalance and inherent soil property. Phosphorus (P) is one of the critical elements that limit plant production, particularly in humid and sub humid acid soils [4].

One of the major constraints in finger millet production in Makueni County is soil infertility, particularly P deficiency. Inherent poor soils, continued cultivation, improper use of fertilizers, and poor agricultural management practices have greatly affected the physical, chemical and biological properties of soils in the region. This has resulted to the area of land cultivated under finger millet dwindle over the years as people prefer other crops and its production still low. In order to reverse this trend and achieving higher yields, it requires proper crop-soil nutrition management. Therefore there is need to seek proper application rates of fertilizers especially P which is one of the most essential macro nutrients. Phosphorus (P) is one of six essential macronutrients (N, P, K, Ca, Mg and S) required by plants. Their roots require P as phosphate (Pi) primarily in the form of $H_2P_{O4}^-$ from the soil solution [5]. The concentration of Pi in the soil solution is often low (10 to 20µM) [6] and consequently, the supply of Pi to the root surface by diffusion is slow [7]. Incidentally is documented as one of P unavailable and macronutrients in the soil [8] and frequently limits plant growth. Therefore there is strong reason for need for the supply of inorganic P fertilizers. Unfortunately inorganic P is unavailable in nature and it is estimated that cheap P source is likely to be exhausted within 60-90 years [9].

In addition, excess P added to crops may lead to pollution of local water resources, leading eutrophication. Therefore, P fertilizer should be used judiciously. This might be achieved by developing or selecting crops that either acquire P or use P more efficiently, so that less P fertilizer is required or developing more precise methods to monitor crop status, such as that of P fertilization can be managed efficiently [9].

Research results have shown that 50-80% of P applied as fertilizer is adsorbed by soil; however, the amount of P needed to achieve maintenance of its adequate status in soil has not so far been known [10]. Information on how phosphorus influences soil properties which in turn impact on finger millet production in the region is scanty and limited. In order to maintain or replenish soil fertility and for prescribing fertilization, monitoring of change in nutrient status of the soil becomes very important necessitating the current study.

2. MATERIALS AND METHODS

2.1 Site Description

The study was carried out at the Kenya Agricultural and Livestock Research

Organization, Kiboko crops research station in Makueni county which lies within longitudes 37° 37' 60 E and latitude 2°13' 0 S with an elevation of 975 metres above sea level. The climate of the area is semi-arid tropical with mean annual maximum temperature of 28.6℃.

2.2 Experimental Layout and Design

The experiment was laid out in a randomized complete block design fitted in a factorial arrangement with four levels of phosphate fertilizer which was supplied as Triple Superphosphate as follows: 0, 12.5, 25 and 37.5 kg ha^{-1} P_2O_5 where 0 kg ha^{-1} P_2O_5 was the control and three finger millet varieties: U-15, P-224 and Kat-FM1 where Kat-FM1 was the local check and the treatments were replicated three times. Each experimental plot measured 4 by 2 metres and a 1m pathway maintained within each plot. TSP was applied at planting along the furrows and mixed with the soil to avoid direct contact with seeds when drilled. All field management operations were then done as recommended for finger millet production.

2.3 Soil Sampling, Analysis and Data Collection

Soil samples were obtained from three points on the furrows in each experimental unit using a soil auger in a zigzag pattern at a depth of 0-30 cm before planting for each season and used to characterize the initial soil status of the experimental field. After harvesting, soil samples were collected in each plot from three spots on the rhizosphere of middle three rows to analyse the balances after each cropping season. The soil pH was determined electrometrically as described by [11]. Total nitrogen was determined by the Macro Kjedahl method [12]. Available phosphorus was determined by the Olsen method [13]. Organic carbon was determined using the Walkley-Black procedures [14]. The grain yield from a net plot of 3 m^2 from every experimental unit was weighed at 13.5% moisture content and extrapolated to yield per hectare.

2.4 Statistical Analysis

The difference in the soil chemical characteristics was calculated between the analytical results at harvesting and that before planting. Analysis of variance (ANOVA) was performed using GenStat statistical software Version 15.1 to test treatment effect at 5% level of significance. The means were separated using the Duncan Multiple Range Test (DMRT) where significant differences between treatments were observed.

3. RESULTS AND DISCUSSION

3.1 Soil pH

The soils were predominantly alkaline before application of P fertilizer at 9.0 for the short rains season and 9.26 during the long rain season. The pH of the two seasons did differ significantly *($p<.05$)* in their response to application of phosphorus with a decrease observed in both seasons but relatively higher during the long rains. P rates had a significant influence on the pH where 25 kg ha^{-1} P_2O_5 and 37.5 kg ha^{-1} P_2O_5 elicited the highest net decrease of -0.68 and -1.36 during the short and long rains respectively (Table 1). The control showed the least net change during the long rains season. The same was observed with the lowest with the 12.5 kg ha^{-1} P_2O_5 during the short rains. Interactions between variety and the phosphate rates were revealed with the highest rates of P supply on each variety, where the most negative net balance for weighted values of varieties tested with 37.5 kg ha^{-1} P_2O_5 rate. These were observed in both seasons.

This was probably due to phosphoric acid in the phosphate fertilizer which had an acidifying effect on the soil rhizosphere whereby it releases H^+ ions progressively to the soil and acidifying the soil surrounding the band. Similar findings were

Table 1. Response of soil pH to phosphate rates in Makueni County

Kg ha^{-1} P_2O_5	Short rains			Long rains		
	Before planting	After harvesting	Net Gain/Loss	Before planting	After harvesting	Net Gain/Loss
Control	9.00	8.70	-0.30c	9.26	8.71	-0.55c
12.5	9.00	8.76	-0.24c	9.26	8.05	-1.21b
25.0	9.00	8.44	-0.56b	9.26	8.09	-1.17b
37.5	9.00	8.32	-0.68a	9.26	7.90	-1.36a

Values followed by same letters within the column are not statistically different reported by [15], who found that after application of monocalcium phosphate fertilizer, it reacts with moisture to form phosphoric acid which progressively releases hydrogen ions to the soil leading to an acidifying effect around the band. During the long rains season the greater decrease in the soil pH could be attributed to the poor rainfall and distribution during the growing period of the crop. This enhanced acidity because moisture is required for the increased uptake of P and release of exchangeable bases that raises the pH.

3.2 Soil Extractable P

Application of P led to the increase of available P in both seasons with 37.5 kg ha^{-1} P_2O_5 treatment indicating the highest net increase of 11 ppm and 9 ppm during the long and short rains seasons respectively (Fig. 1). This finding confirms that P fertilization is of extreme importance in deficient soils for increasing available P. The P was partially taken up by plants but it is well known to have residual effects on the top soil. The control did show low net increase in the amount of available soil P which indicates that alkaline soils tend to turn insoluble forms of P into soluble forms during crops growth period especially if conditions are favorable.

It has been found that fixed P is not entirely lost but it becomes slowly available to crops over several years depending on soil and P-compound type. This finding is consistent with those by [16] who found that phosphorus is held firmly and hence unavailable to plants until the organic material in the soil environment decomposes, he concluded that plant roots and rhizosphere organisms which are found around plant roots excrete phosphatase enzymes capable of hydrolyzing some organic phosphate compounds, releasing inorganic phosphate for absorption by the plants. The role of acid or alkaline phosphatase is key for its availability (for the present case it is alkaline phosphatase). This can be also attributed to the residual effect of P fertilizers applied in earlier seasons which are converted back to available form.

3.3 Total Soil N

The initial total N for both seasons had an average of 0.03% which was low and after application of P there was considerable increase in the amount of total N in the soil. The highest net increase of 0.052% was observed on the 37.5 kg ha^{-1} P_2O_5 rate during the short rains season as shown on Fig. 2. The control had the lowest increase of total N in the soil during the

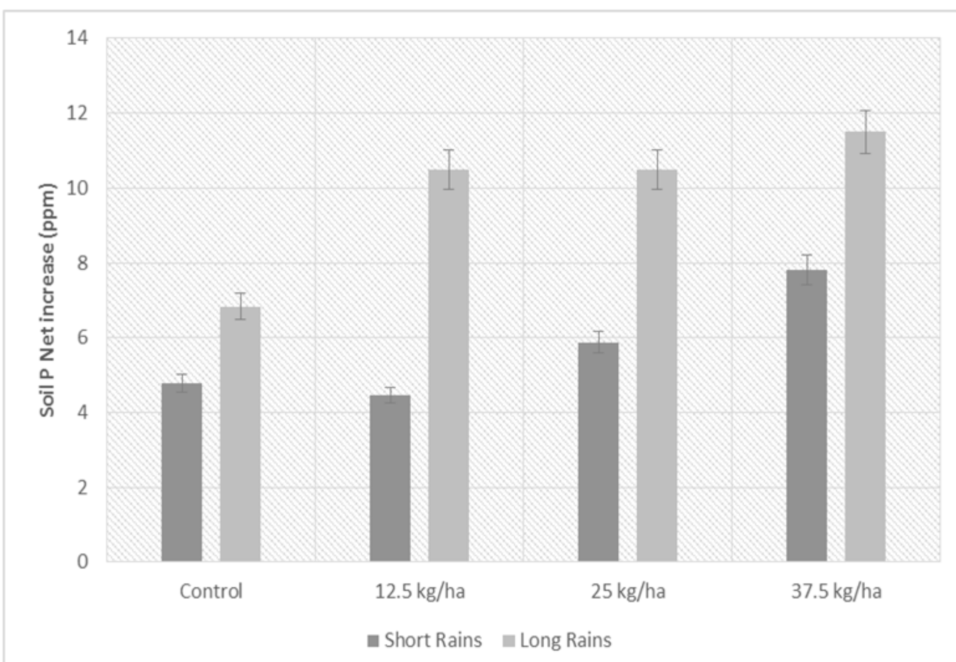

Fig. 1. Net increase on the soil phosphorus during the short and long rains in Kiboko due to phosphate rates

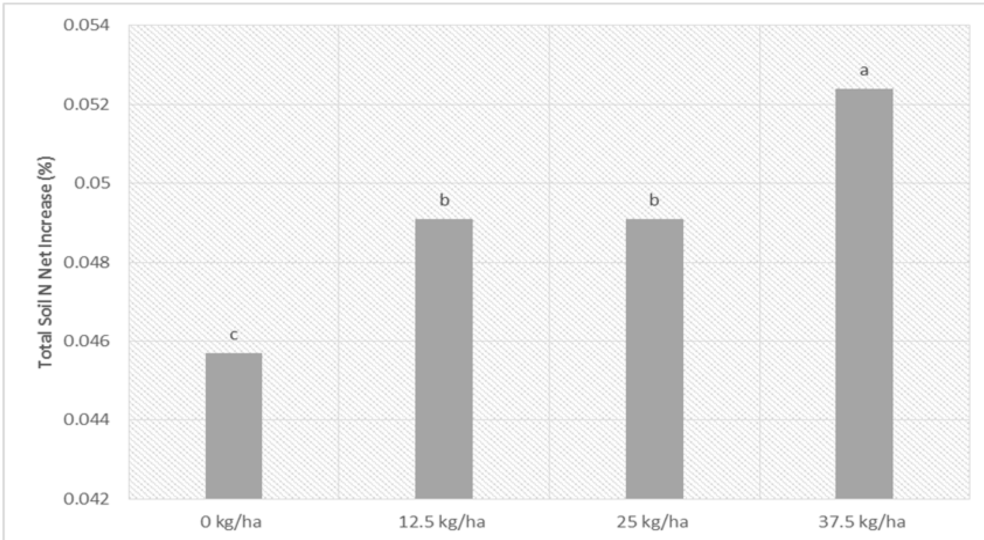

Fig. 2. The influence of phosphate levels on the total nitrogen net increase during the long rains in Makueni soils

same period but the increase might be due to the decomposition of crop residues from the previous seasons which could be done through mineralization via biological activity and coinciding with earlier reports [3,17] that soils that are regularly under cultivation accumulate organic N in the decomposed crops until they reach a steady-state condition where they become available to plants. During the short rain season there were no significant differences between the treatments on the net total soil N because of optimal availability of P in the study soils.

The carbon to nitrogen ratio for the short rains ranged between 6:1 and 8:1 while the long rains ranged from 9:1 and 11:1 where the alkaline soils highly favored decomposition of the crop residues thereby releasing greater amount of organic carbon that enhances release of mineral N.

3.4 Total Organic Carbon

The control treatment had the least increment during the long rains as shown in Fig. 3. On the contrary the P treatments led to increase in organic carbon and the net gain became greater as the rate increased. The peak was observed at the 25 kg ha^{-1} P_2O_5 level after which the increase in P rates led to the reduction of organic carbon. During the short rains, the treatments showed inconsistent trend with the control and the 37.5 kg ha^{-1} P_2O_5 having the highest net increase as indicated on Fig. 3. This could be due to the decomposition of residual materials in the soils that had different rates effecting the treatments differently. There was a greater increase of the soil organic carbon during the long rains season compared to the short rains. The greater increase of the organic carbon during the long rains is due to the soil pH which was strongly alkaline prior to planting and in turn enhanced decomposition of materials in the soil. This has been revealed in other findings [17] who found that the pH can affect the soil environment through influence on sorption potential, cation availability and microbial degradation rates. Similar consistent patterns have been identified in other studies [18,19] who found that the enhanced soil acidity may act directly on the functioning of the microbial community which increases the carbon input through biomass production during the crops growth. The increase in the total organic carbon can enhance fertility, productivity and sustainability of agro-ecologies because it acts as a basis for the global carbon cycle.

3.5 Grain Yield as Affected by P Supply amongst Finger Millet Varieties

The interaction between the phosphate rates and variety were revealed for both seasons with the combination between U-15 and 25 kg ha^{-1} P_2O_5 indicating the highest yield during the short rains with 3.71 t/ha and 2.44 t/ha during the long rains (Fig. 4). Other previous work [20,21] are in agreement with current results where varietal differences were observed in yield in response to P. This may imply of U-15 superiority on P uptake and assimilation compared to the other two especially given phosphorus role of optimum P in energy provision for seed formation and grain filling. Reduction of yield on the highest phosphate rate might be due to lowered translocation of other nutrients due to the toxicity by excess phosphorus. There could be possibility of higher P indirectly interfering with growth by affecting uptake of micronutrients as earlier reported in nightshades accessions supplied with different P rates [22] where application beyond 60 kg ha^{-1} led to a decline in the leaf fresh weight, leaf area, number of secondary buds and plant height. Excessive P on yield depression has also been reported in maize [23], who found that by increasing the phosphorus rate beyond 40 kg ha^{-1} there was a decline in the grain yield.

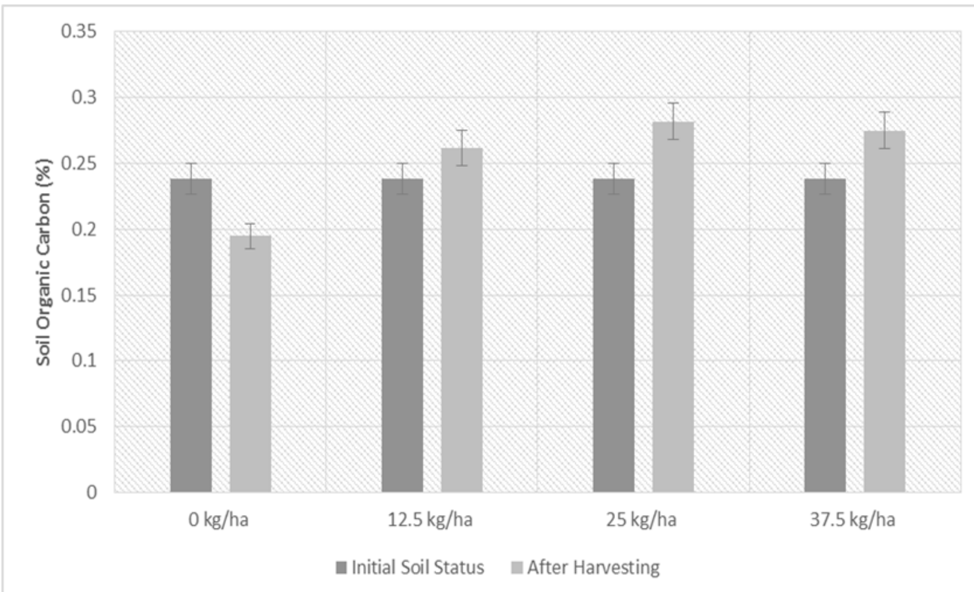

Fig. 3. Phosphorus levels effect on total organic carbon during the short rains in Makueni soils

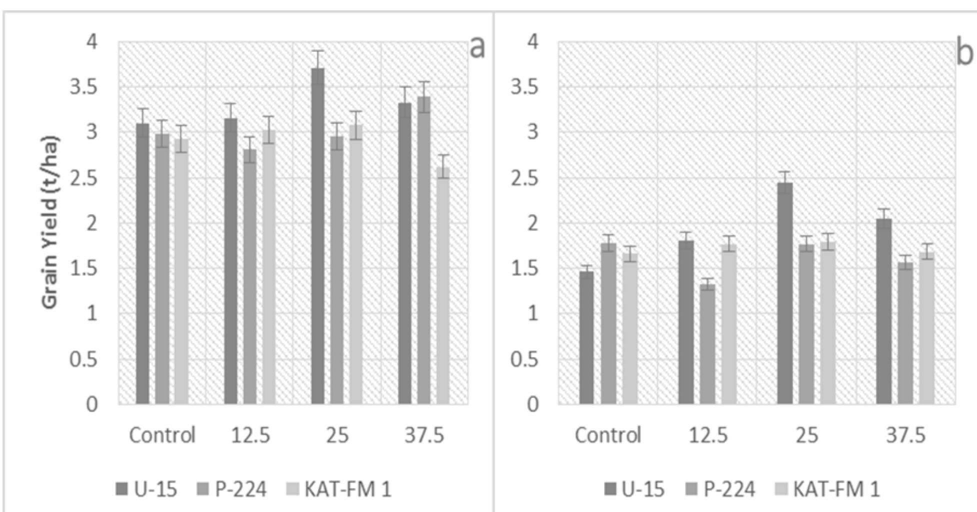

Fig. 4. Interaction effect between phosphate rates and variety on the grain yield during the short rains (a) and long rains (b) in Makueni

The combination between improved variety U-15 and 25 kg ha^{-1} P_2O_5 rate led to significantly higher yields of up to 3.7 tonnes per hectare. This also improved the soil quality by reducing the alkalinity in the soil where higher pH values tend to accumulate more calcium which has a negative effect on the available phosphorus through fixation.

4. CONCLUSION

The results from this study shows that the application of phosphorus fertilizer improved the soil quality by reducing the alkalinity in the soil where higher pH values tend to accumulate more calcium which negatively affects available phosphorus through fixation and also increased total soil N and soil organic carbon. The phosphate application of 25 kg ha^{-1} P_2O_5 rate under variety U-15 forms the basis of recommendation for maximum productivity of the crop in the study region.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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