

Nitrogen and Phosphorus uptake and Partitioning in Finger Millet as influenced by Phosphorus fertilization

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

ABSTRACT

Finger millet (*Eleusine coracana*) production in Eastern Africa remains low due to a variety of factors including soil nutrient depletion. As intensive row-crop production evolves, improvements in managing soil nutrient quantity and availability of less renewable nutrients like P becomes increasingly important. The yields in Kenya are typical of low input systems ranging below 1.0 t ha⁻¹ against a potential of 5.0 t ha⁻¹ in a season. In an attempt to overcome this constraint, On-station experiments were conducted at the Alupe research station during the long and short rain seasons of 2015 to investigate the influence of phosphate fertilizer rates (0, 12.5, 25 and 37.5 kg ha⁻¹ P₂O₅) on nutrient uptake and partitioning in finger millet. Partitioning of N and P was significantly influenced ($P < .05$) by phosphate rates and variety. Most phosphorus and nitrogen content was partitioned to the grains (>30%) while the least to the roots (<19%). Variety U-15 had the greatest partitioning of nitrogen to the grains while the local variety, Ikhulule had the least. Application of phosphorus led to increase in the nitrogen and phosphorus uptake in finger millet with the most in the grains with a maximum of 106.5 kg ha⁻¹ on the 37.5 kg ha⁻¹ P₂O₅ rate during the short rains while the roots had the lowest uptake with 16.9 kg ha⁻¹ and 22.1 kg ha⁻¹ in the long and short rains seasons respectively on the control. This study on nutrient use provides an opportunity to further improve P fertilization to specific rates in relation to crops needs as farmers will be assured of greater yields, profitable and sustainable production. Limited use of P fertilizer restricts the uptake of phosphorus and nitrogen as well as the balance in partitioning and recommends application of 25 kg ha⁻¹ P₂O₅ with improved varieties.

Keywords: *Eleusine coracana*; nutrient depletion; renewable nutrients; profitable.

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25 1. INTRODUCTION

26 Finger millet (*Eleusine coracana*) is an important food crop grown in low input farming
27 systems by resource poor farmers in Eastern Africa. These farmers frequently suffer from
28 high poverty, food insecurity, hunger and malnutrition [1]. Though limited attention is given to
29 the crop by the national research systems, it is highly nutritious, it is hardy to abiotic and
30 biotic stress compared to most cereals, has high malting quality only second to barley, and
31 has good storability with minimal damage from storage pests and can be a great remedy to
32 the challenges faced by smallholder farmers. The crop is grown on approximately 77, 890 ha
33 in Kenya [2] with a yield range of 500-1000 kg ha⁻¹ against a potential of 5,000 kg ha⁻¹ [3].
34 With appropriate research and proper dissemination of information to farmers, it is possible
35 to achieve 3-4 t ha⁻¹ as reported from on-farm and on-station studies in Kenya [4]. One of the
36 major constraints in finger millet production is soil infertility. Improved agronomic
37 management practices have aimed at matching plant nutritional needs with nutrients from
38 the soil and fertilizer sources. These practices allow sustainable use of fertilizers by
39 replacing removed nutrients without excessive application rates. Nutrients with high nutrient
40 harvest index values remove more of that nutrient from the field than nutrients with low
41 nutrient HI values and suggest a looming soil infertility crisis if adequate adjustments are not
42 made in usage rates of fertilizers. It is suggested that phosphorus, the second most widely
43 limiting nutrient in soil after nitrogen [5, 6], is a critical macronutrient for plant growth and
44 development, particularly in tropical and subtropical soils, P deficiency is a major limitation to
45 crop production [7]. Previous report by Stewart and Tiessen [8] had observed that less than
46 1 % of soil P is available for plant uptake, which is as a result of strong adsorption of
47 phosphate by iron and aluminium oxides. There is a great disparity in distribution of
48 phosphate uptake rate (Pi) between plant cells (mM) and soil solution (μM) [9]. Extremely
49 low levels of available phosphorus in the rhizosphere therefore make it one of the major
50 growth-limiting factors in many ecosystems [10]. The concentration of available Pi in soil
51 seldom exceeds 10 μM [11]. According to Smaling et al [12], phosphorus has a significant
52 role in sustaining and building up soil fertility, especially under intensive system of
53 agriculture. Thus, its deficiency becomes an important chemical factor restricting plant
54 growth in soils.

55 While N is the most limiting nutrient generally in soil, Dolve et al. [13] has shown that
56 deficiency of soil P reduces the efficiency of N use by crops. Experiment conducted on
57 tomatoes reported the differences and similarities in the growth response of tomato plants to
58 N and P limitation, and to their interaction [14]. These results suggest that the decrease in N
59 concentration with increasing P limitation may be mediated by a decrease in leaf cytokinin
60 levels and is less likely due to decreased energy availability at low P conditions. Dry-mass
61 partitioning to the roots was closely linearly related to the leaf reduced-N concentration.
62 However, treatments that were severely P limited deviated from this relationship. Case
63 studies have been conducted to examine responses of ecosystem biomass production to P
64 addition, which vary significantly among different studies or ecosystems [15]. For instance,
65 biomass has been reported to increase [16], decrease [17], or to change insignificantly [18]
66 in response to external P input. According to Li et al. [19], such various and inconsistent
67 results may be due to different ecosystem types, P fertilizer forms, or P addition rates. There
68 was therefore, need to extend these investigative efforts to include other crops such as
69 cereals and particularly finger millet.

70 While fertilizer recommendation has become increasingly important to address the poor
71 state of soils in Eastern Africa, information used to estimate P and N uptake, utilization and
72 partitioning among organs under varying P is limited, especially on finger millet. Although
73 nutrient management is a complex process, understanding the allocation of nutrients by
74 finger millet crop under P stress presents opportunities to optimize fertilizer rates. This
75 realization therefore led to the present study which aimed at evaluating the optimal

phosphorus fertilizer rates that is effective in P and N allocation to the grains to improve yields and quality of finger millet and to an extent, reduce fertilizer waste and environmental pollution.

2. MATERIAL AND METHODS

2.1 Site description

Two field experiments were conducted during the 2015 long and short raining seasons at Alupe Crops Research Station in Busia County. The site lies on Latitude 0° 30" N and Longitude 34° 07' 50.02" E with an elevation of 1157m A.S.L. The top soil of the experimental site was sandy clay loam with nutrient content of 0.08% N, 8 ppm P, 0.74% organic carbon and 0.3 Meq/100 g exchangeable acidity [20].

2.2 Experimental layout and design

The experiment was laid out in a Randomized Complete Block Design in Factorial arrangement with three replicates. The treatments comprised of four phosphate fertilizer rates as triple superphosphate (0, 12.5, 25 and 37.5 kg ha⁻¹ P₂O₅) and three finger millet varieties (U-15, P-224 and a local check, Ikulule). The experimental units measured 4 m long and 2 m wide with a 2 m pathway between them. During the onset of each season the study field was ploughed, re-ploughed and harrowed and demarcated into the 36 experimental units. Sowing during the long rains was done on March 30th and 27th September for the short rains by drilling. The triple superphosphate was applied according to the specific treatments and no fertilizer was applied on the control. After four weeks Urea was top-dressed in a blanket rate of 50 kg ha⁻¹ N. The crop was harvested at physiological maturity on 11th August 2015 and 15th February 2016 for the long and short rain seasons, respectively.

2.3 Plant tissue analysis and data collection

At harvesting, all parts from ten plants from each experimental unit were separated from the plant and dried in an oven at 75°C to constant weights which were then weighed and recorded. Plant samples were then analyzed for P and N contents. Total phosphorus was determined by the molybdenum blue colorimetric method [21] and total nitrogen was determined by the micro-Kjeldahl digestion [22]. Leaf, stem, panicle and root phosphorus and nitrogen uptake were calculated by multiplying the nutrient concentration by dry weights of the respective plant parts. The total amount of P and N uptake was calculated by summing the content of each element in all the plant parts and extrapolated by the amount of nutrient in plant material by the biological yield in kilograms per hectare. Partitioning (%) was calculated by equating the nutrients concentration in each plant part as a fraction to the total uptake by the plant and converted into a percentage.

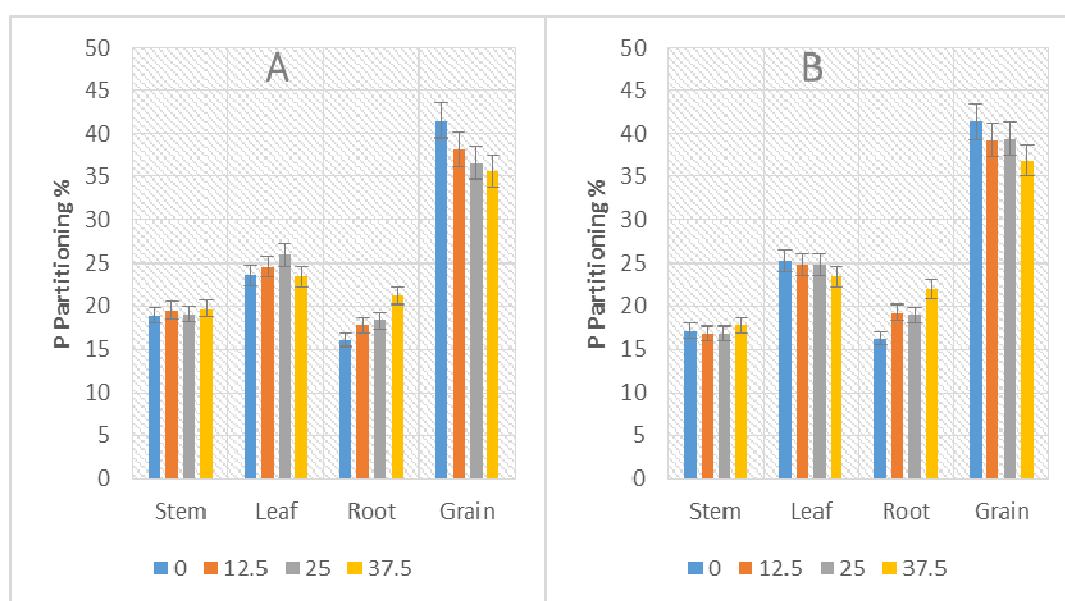
2.4 Statistical analysis

The data collected was subjected to Analysis of Variance (ANOVA) to test significance due to treatments and where found Fisher's Protected LSD test was used to separate the means at 5% probability using GenStat statistical software Version 15.1.

3. RESULTS AND DISCUSSION

3.1 Phosphorus uptake and partitioning

119 The partitioning of phosphorus content in the plant parts differed significantly for both
 120 seasons (Fig. 1). There were also differences on the interaction between the phosphate
 121 treatments and varieties on the uptake of phosphorus (Table 1) and partitioning of P in the
 122 finger millet plants. The grains contained most of the phosphorus with over 41% allocated to
 123 the grains during the short rains and 42% during the long rains in the control treatment (Fig.
 124 1). Jungk and Barber [23] also reported that maize utilization of applied P to the grain was
 125 greater at low P application rate, indicating that P efficiency decreases as application rate
 126 increases. There was 26% P partitioned to the leaves during the short rains in the 25 kg ha⁻¹
 127 P₂O₅ rate and 25% P on all the treatments except the highest rate which had 24% during the
 128 long rain. On the other hand, the stems contained 19% P during the short rains and 17% P
 129 during the long rains with no significant differences between the P treatments, while the
 130 roots contained the least content of P for both seasons with 16% during each season.
 131 Interestingly, there was a clear trend in allocation of P to roots and grain, where the roots
 132 exhibited the highest partitioning of P with the highest rate of P application as shown on Fig.
 133 2.

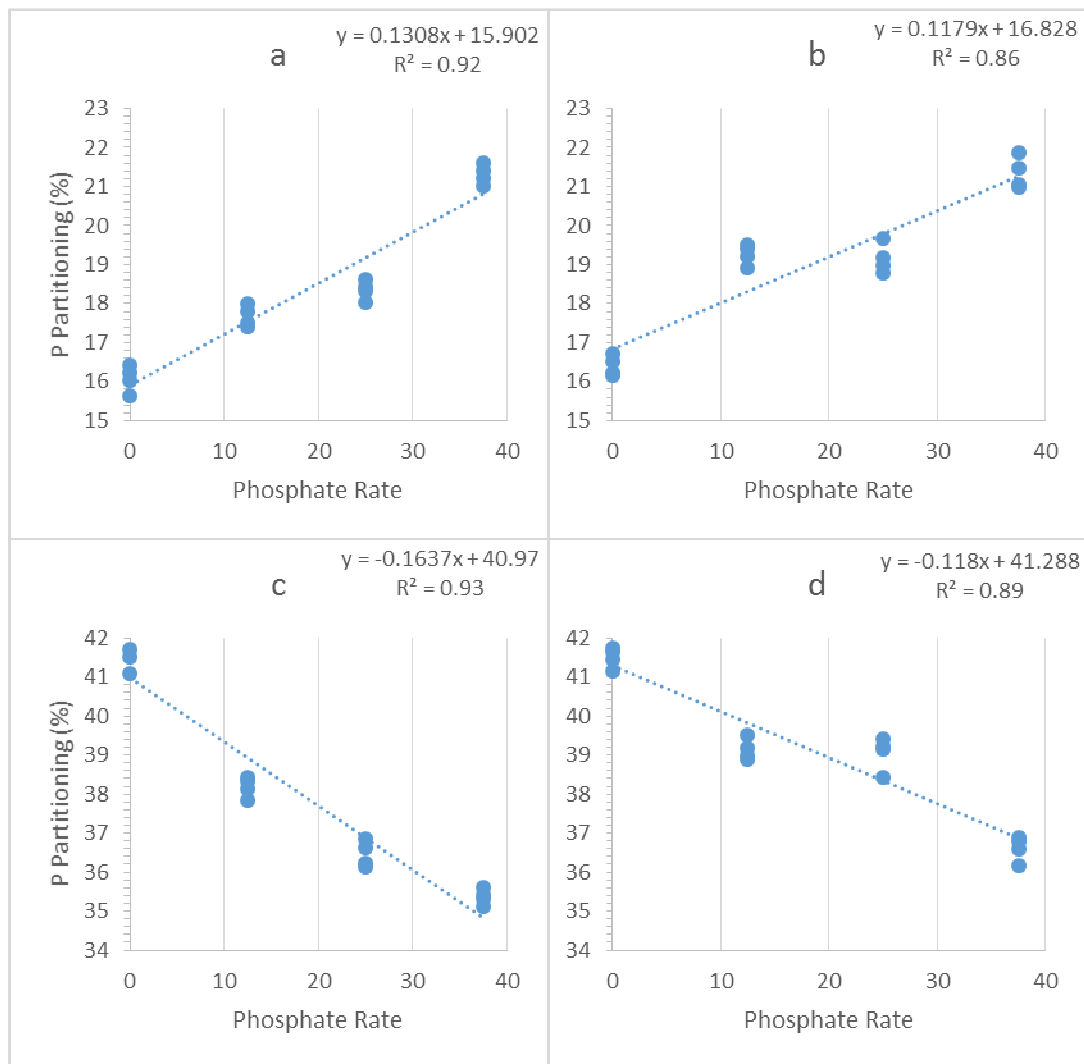


134 **Fig. 1. The amount of P partitioned to the stem, leaf, root and grain of finger millet**
 135 **during the short (A) and long (B) rainy seasons in Alupe.**

136 The partitioning of P follows a steady and predictive uptake rate from V6 through R6 due to
 137 the plants mechanism to switch P partitioning by remobilization to reproductive parts at the
 138 expense of vegetative organs. Phosphorus requirement increases steadily after flowering
 139 and during ripening periods of cereals and during grain formation, translocation of P to the
 140 grain has been documented to be about 75% of the total P in the above ground parts [24].
 141 Under P deficiency, the amount available to the plant during grain formation definitely
 142 influences the P content of the grain. In a study on corn, similar findings were reported
 143 where nutrients especially P was found to be highly mobile and begins translocation to the
 144 grain at the R2 stage [25]. Phosphorus uptake was observed to increase with increasing
 145 rates in the finger millet crop. The control had more P channeled to the grains compared to
 146 the other parts. This is because the grains are the main sink of P in finger millet and under
 147 limited P conditions the plants channels most of the P for grain filling. However, the plants
 148 had a lower total P uptake compared to the applied treatments because of the reduced
 149 growth due to the low P efficiency under suboptimal P conditions in the soil. This could be

150 due to its relative unavailability initially, when applied to phosphorus deficient soils. Similar
 151 findings were reported by Fohse et al. [26].

152



153 **Fig. 2. Linear regression characterizing the relationship between applied phosphorus**
 154 **and partitioning percentage of P in the root during the short (a) and long (b) rain**
 155 **seasons, and in the grain during the short (c) and long (d) rain seasons in Alupe.**

156 The allocation of P on the different plant parts was significantly influenced by the interaction
 157 between variety and phosphate application rates for both seasons. The combination
 158 between the highest rate of 37.5 kg ha⁻¹ P₂O₅ and P-224 elicited the greatest partition of
 159 phosphorus to the grains with 106.5 kg ha⁻¹, leaves and stems during the short rains season
 160 (Table 1). However, the same combination was also significantly the same to the
 161 combination between P-224 and 25 kg ha⁻¹ P₂O₅ that had 95.6 kg ha⁻¹ phosphorus uptake in
 162 the grains during the short rains. The control showed the lowest phosphorus uptake in all the
 163 plant parts for both seasons in all varieties where the lowest (16.9 kg ha⁻¹) observed under
 164 variety U-15. Phosphorus concentration in grain was reduced when there was limiting P in
 165 the soil.

Table 1. Interaction effect between phosphate rates and variety on the phosphorus uptake in kg ha⁻¹ in Alupe

Variety	kg ha ⁻¹ P ₂ O ₅	Stem		Leaf		Root		Grain	
		2015 SR	2015 LR	2015 SR	2015 LR	2015 SR	2015 LR	2015 SR	2015 LR
U-15	0	29.9 ^c	18.8 ^a	39.4 ^d	24.1 ^a	22.1 ^d	16.9 ^d	66.2 ^d	39.4 ^e
	12.5	37.0 ^b	20.4 ^a	49.3 ^c	25.7 ^a	28.2 ^c	18.6 ^d	82.7 ^b	40.7 ^e
	25	38.6 ^b	26.4 ^a	52.0 ^c	38.5 ^a	31.9 ^b	27.5 ^b	77.2 ^c	61.6 ^b
	37.5	41.7 ^b	22.6 ^a	55.5 ^c	32.5 ^a	31.2 ^b	23.6 ^c	78.1 ^c	45.3 ^d
P-224	0	31.4 ^{bc}	19.1 ^a	40.9 ^d	31.2 ^a	18.8 ^e	18.1 ^d	65.9 ^d	49.3 ^d
	12.5	33.8 ^{bc}	22.8 ^a	45.1 ^d	35.8 ^a	21.0 ^d	23.9 ^c	75.6 ^c	55.3 ^c
	25	48.8 ^b	26.5 ^a	66.4 ^b	40.4 ^a	31.2 ^b	32.3 ^a	95.6 ^a	65.8 ^b
	37.5	59.5 ^a	29.0 ^a	79.4 ^a	41.1 ^a	32.2 ^b	27.8 ^b	106.5 ^a	64.1 ^b
Ikhulule	0	27.2 ^c	25.6 ^a	32.7 ^e	37.8 ^a	20.4 ^d	26.9 ^b	58.6 ^d	62.0 ^b
	12.5	39.5 ^b	30.9 ^a	52.7 ^c	43.0 ^a	32.0 ^b	32.2 ^a	84.6 ^b	72.5 ^a
	25	43.8 ^b	31.2 ^a	60.9 ^b	43.6 ^a	34.3 ^a	31.2 ^a	85.7 ^b	73.5 ^a
	37.5	39.7 ^b	22.3 ^a	59.6 ^b	31.5 ^a	34.3 ^a	26.0 ^b	90.3 ^b	43.6 ^d
Significance	V	.043	.26	.006	0.07	<.001	.227	.347	.356
	P	.002	.04	.001	.005	<.001	<.001	.04	<.001
	V×P	<.001	.08	.001	.072	<.001	<.001	.025	.001

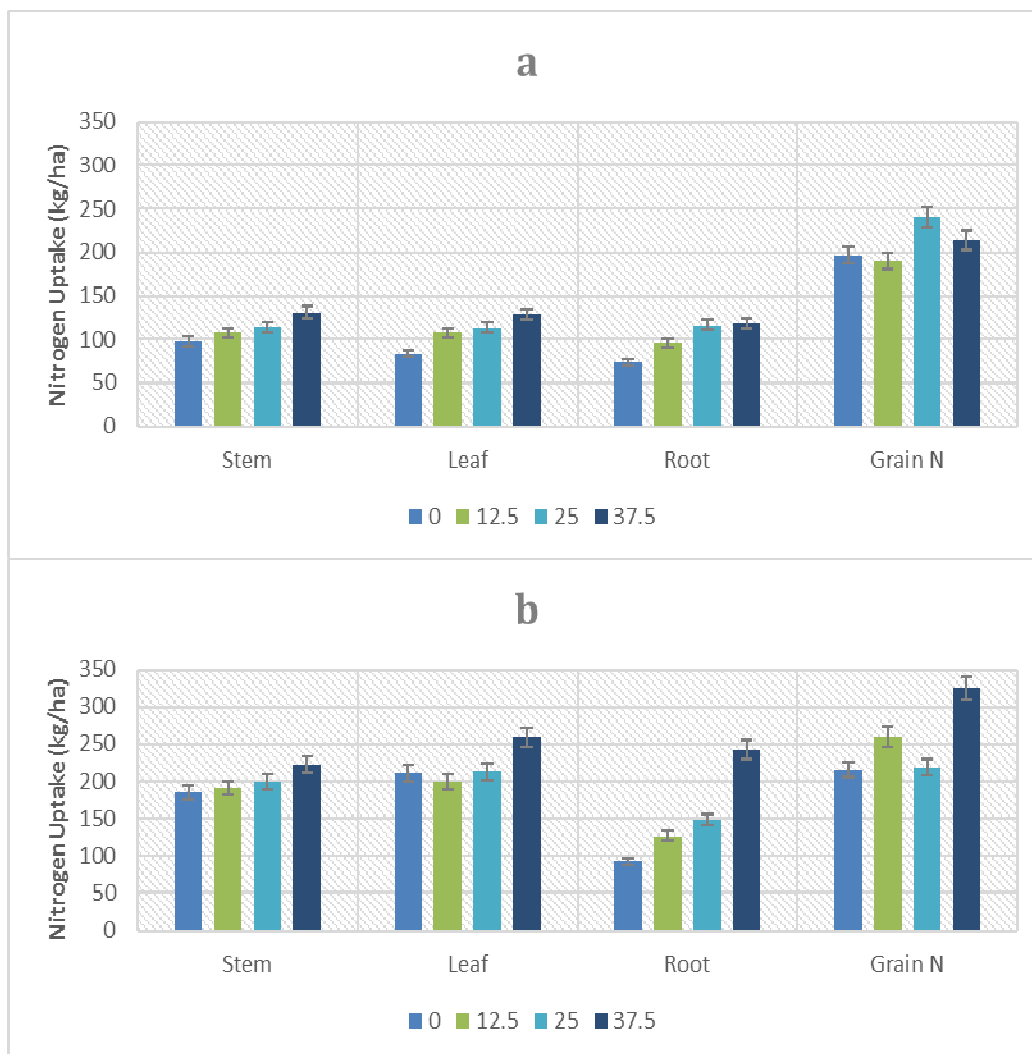
Values followed by same letters within the column are not statistically different

This is due to the low supply of energy to meet the requirement by plants to take up nutrients from the soil and translocate them through the plant. Varietal differences were not observed for both seasons on the uptake of P in the grains but on the roots Ikhulule was superior owing to its extensive root network while P-224 was superior in the leaves and stem. In converting the P uptake to economic yield P-224 seem to do better than the other varieties and this might be partly due to greatest uptake on the leaves that apparently associated with similar N (Fig. 2) that probably had a bearing on photosynthetic rate, leading to greater metabolic activity by the plants. The proportion of P concentration in the grains was relative to the total plant uptake and provided an estimate of partitioning and remobilizing efficiency and nutrient harvest index as observed in the combination between 37.5 kg ha⁻¹ P₂O₅ and P-224. This indicates that the lower rate of 25 kg ha⁻¹ P₂O₅ which was insignificantly different from the highest rate in uptake of P is more sustainable and reduces luxurious consumption by plants or loss to the environment. Lack of P fertilization heavily impacted on the plants by increasing stress that generally lowered the quantities of the total nutrients partitioned and remobilized in the plant.

3.2 Nitrogen uptake and partitioning

Phosphorus application significantly increased the uptake of nitrogen for both seasons in Alupe as shown on Fig. 3. The Nitrogen partitioning was significantly influenced ($P<.05$) by phosphate fertilizer rates and variety in both seasons. The grains contained the most nitrogen concentration with over 30% among the phosphate treatments and varieties. The nitrogen uptake increased with increasing P rates in all the plant parts (Fig. 3) with the highest rate having the greatest nitrogen uptake for both seasons except in the grains for the short rains where the 25 kg ha⁻¹ P₂O₅ had the greatest uptake. The leaves and stems contained between 23-30% N and the roots contained the least amount of nitrogen with less

193 than 16% N in both seasons. Differential nitrogen partitioning was also reported by Graciano
 194 [27] with *Eucalyptus* spp. and there were clear difference among organs. According to the
 195 author [27], the nitrogen uptake and partitioning was even more influenced by P rates than
 196 the N supply. Their findings are in concurrence with the current study, where N uptake and
 197 partitioning increase with P rates.



198 **Fig. 3. The effect of phosphate rates on the uptake of nitrogen in plant parts of finger**
 199 **millet during the short rains (a) and long rains (b) in Alupe.**

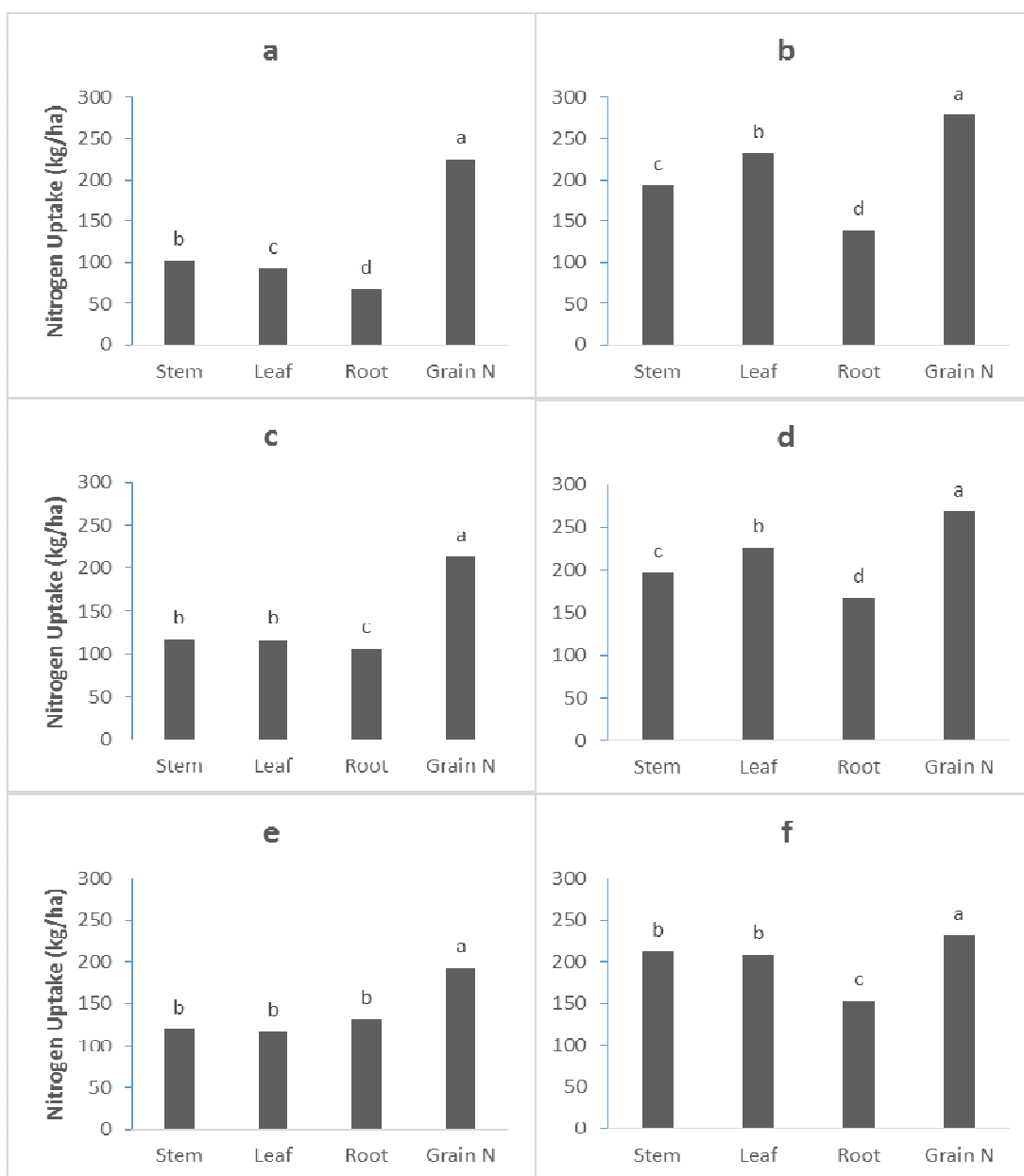
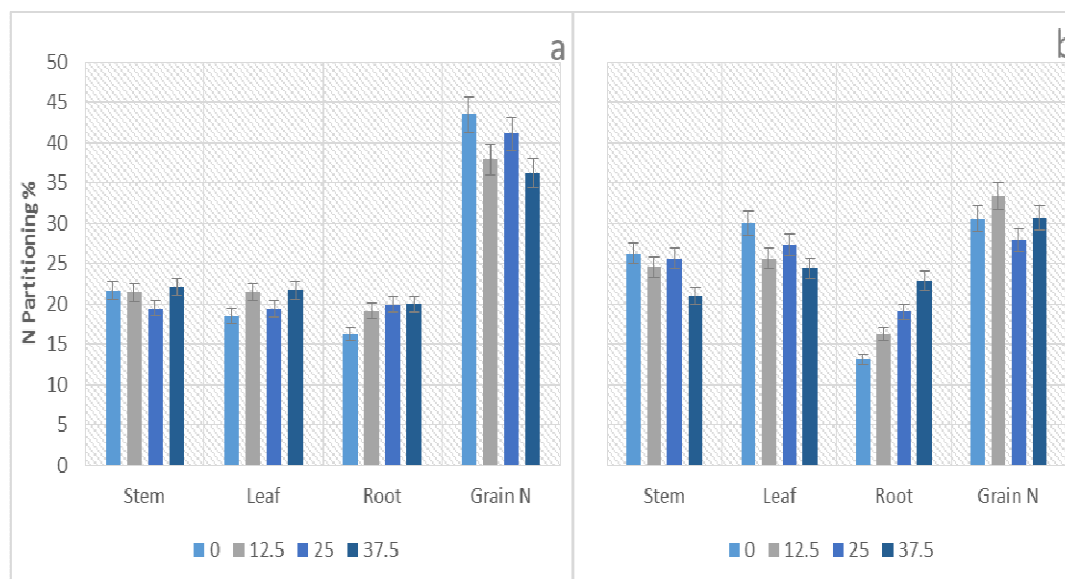


Fig. 4: Partitioning and uptake of nitrogen in plant parts of finger millet varieties U-15 (a & b), P-224 (c & d) and Ikhulule (e & f) during the short and long rains respectively in Alupe.

The improved varieties U-15 and P-224 exhibited the highest partitioning rate of nitrogen to the grains for both seasons compared to the local variety, Ikhulule (Fig. 4). Variety U-15 did have the lowest uptake of nitrogen in the leaves, stems and roots for both seasons but proved to be the best by partitioning most of it to the grains compared to other organs for both seasons. Increased plant N content could also be higher due to the mineralization of organic N which was found to increase due to phosphate fertilizer application. The total nitrogen uptake also increased considerably due to the improvement in symbiotic N_2 fixation, because it is well known that if the P nutrition of plants is improved, either through

212 fertilization or biological means, symbiotic N₂-fixation and the plant N contents are improved
 213 [28].
 214 Application of phosphorus significantly ($P<.05$) influenced the partitioning of nitrogen in the
 215 plant parts for both seasons (Fig. 5). The highest partitioning was to the grains but further
 216 increase in the phosphate rates led to a decrease in the amount of nitrogen partitioned as
 217 shown on Fig. 6 while increase of phosphate rate increased the amount of nitrogen
 218 partitioned in the roots.



219 **Fig. 5: The effect of phosphate rates on the partitioning of nitrogen in plant parts of**
 220 **finger millet during the long rains (a) and short rains (b) in Alupe.**
 221

222 This increase in partitioning to the roots with increasing P was also observed with P tissue
 223 partitioning (Fig 2). Phosphorus also improves the root development and this leads to more
 224 uptake of nutrients. However, the control showed the highest N partitioned to the grains than
 225 the P treatments with up to 43% during the long rain season, while having the least nitrogen
 226 partitioned to the roots with 16% and 13% during the short and long rains seasons
 227 respectively. This is due to the plants mechanism to support reproductive growth at the
 228 expense of vegetative growth in low P conditions. Phosphate rates influenced the total
 229 nitrogen uptake in finger millet with applied plots being significantly superior to the control.
 230 Phosphorus leads to elongation of meristematic tissues and since it is a major constituent of
 231 ADP and ATP-the energy currency in metabolic activities in plants, it led to greater
 232 photosynthetic rates which increased dry matter production that accumulated more nitrogen.
 233 These observations conforms to findings by Sharma and Parmar [29]. The highest
 234 phosphorus level did have the highest N uptake in all the plant parts during the long rains
 235 season while the 25 kg ha⁻¹ P₂O₅ treatment had the highest in the roots and grains during
 236 the short rains season. The greater N-uptake with the application of only P is a factor to be
 237 considered in finger millet cultivation plans. The effects of fertilization at planting may
 238 continue to harvest [30] as attested by higher N content, which declines with P application,
 239 therefore, if the uptake of higher amounts of N in P-fertilized stands continues through time,
 240 this could reduce soil N stocks [31] in the soils, particularly under poor soil characteristic of
 241 peasant farmers. The higher N extraction at harvest could affect the sustainability of soil
 242 productivity [32], and this may, necessitate the need to carry out longer term experiments in
 243 order to study the changes in soil nutrient stocks as affected by fertilization with P.

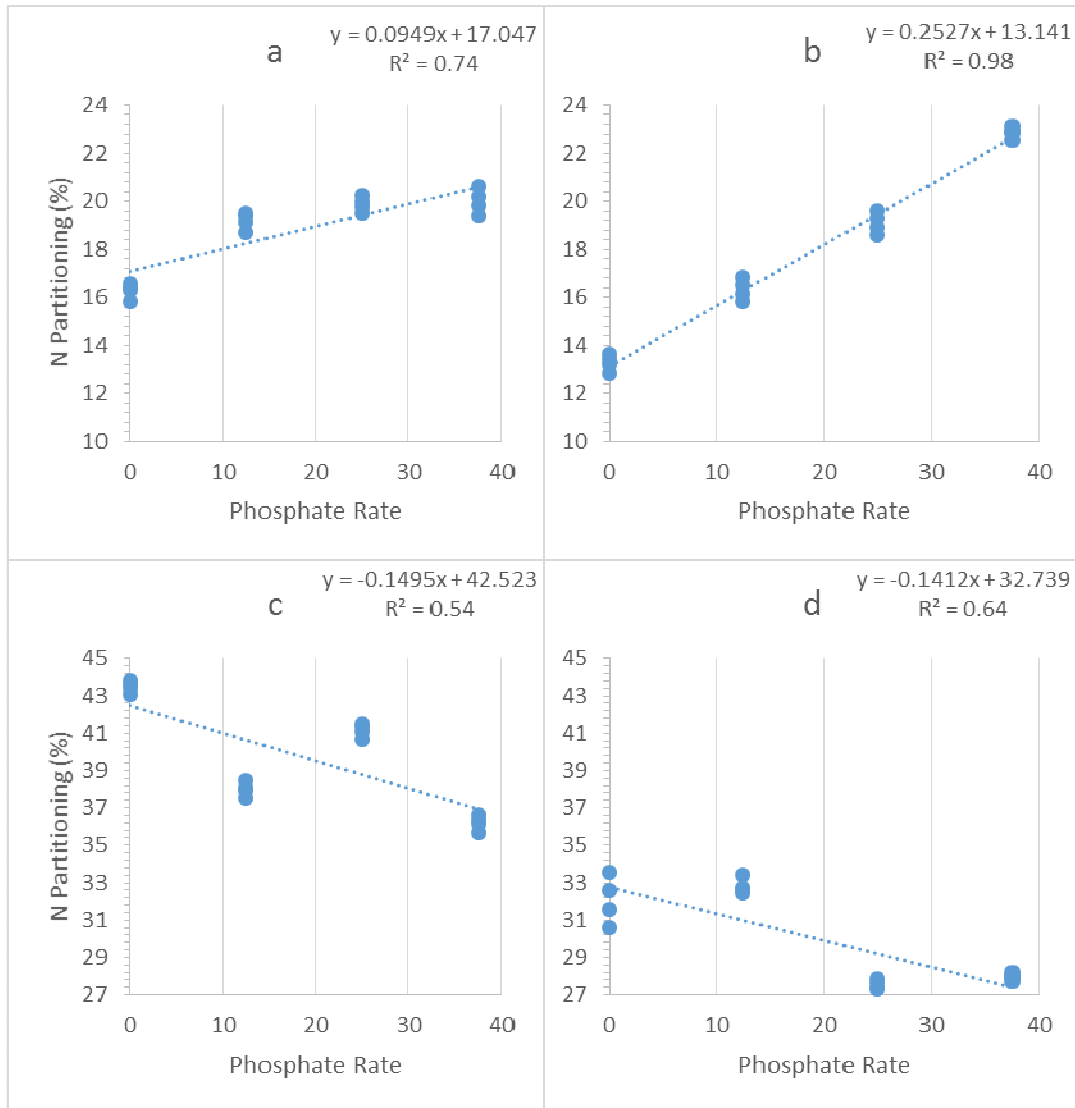


Fig. 6. Nitrogen partitioning percentage as a linear function of the applied phosphorus in the root during the short (a) and long (b) rain seasons, and in the grain during the short (c) and long (d) rain seasons in Alupe.

4. CONCLUSION

Limited availability of phosphorus restricted the uptake of nitrogen and phosphorus as well as the balance in partitioning. The nutrient uptake of P and N increased with increasing P rates and once the efficient use of P nutrient was found limited, the nutrient uptake started to decline. It was also found that phosphorus supply had influenced the uptake and partitioning in different plant organs but this was also dependent on finger millet varieties. There was more partitioning of N and P to the grain where there was limiting P. As more P was added, then most of N and P was allocated to the roots. Since the increase in P supply led to further uptake of P, there is need for caution to avoid continuous cultivation of finger millet as this can lead to excessive extraction of N. The partitioning of P and N to the grain under low P application implies more export of nutrients with grains to the market yet the allocation to roots means that this will be recycled back to the soil. There is need to strike a balance

between grain quality and by extension nutrient export and nutrient recycle and sustainable productivity of the soil where this study recommends 25 kg ha⁻¹ P₂O₅ with improved varieties.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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