https://doi.org/10.46909/journalalse-2021-040
Available online: https://jurnalalse.com

Original Article
Journal of Applied Life Sciences and Environment
Vol. LIV, Issue 4 (188) / 2021: 458-472

HEIGHTENING SORGHUM NITROGEN UPTAKE WHILE MAINTAINING OPTIMAL SOIL NUTRIENT LEVELS THROUGH MINERAL FERTILISER APPLICATION

Riziki MWADALU[1,2*], Benson MOCHOGE[1], Maina MWANGI[1], Harun GITARI[1]

*E-mail: zikiemwa@gmail.com

Received: July 8, 2022. Revised: Aug. 1, 2022. Accepted: Aug. 11, 2022. Published online: Aug. 17, 2022

ABSTRACT. Improving nutrient management of soils is important in subsistence farming systems in the tropics due to declining soil fertility resulting from continuous cropping coupled with inadequate nutrient replenishment. Balancing nutrient inputs with crop removal is crucial in reducing the build-up of nutrients and minimises nutrient losses through different pathways, thus reducing the cost of production. This study aimed at evaluating the effect of N and P fertiliser on sorghum N uptake at Kampi ya Mawe (KYM) in Makueni County and Katumani (KAT) in Machakos County, Kenya. Two factors (nitrogen and phosphorus) each at two levels (0 and 75 kg ha^{-1}) were evaluated, resulting in four treatments, each replicated thrice. At KYM, N content in sorghum tissues increased by 24.2% in comparison with the control following application of N at 75 kg ha^{-1}. At KAT, plots amended with N and P at 75 kg ha^{-1} resulted in the highest N content in sorghum tissues at the three sorghum development stages assessed. At the seedling stage, an increase of 18.8% was observed. Sole N application led to an increase in N content in sorghum tissues of 17.6% at the seedling stage. A positive linear relationship between NO3- N and N content in sorghum tissues was also observed. The study showed that soil N uptake was higher in the early growth stages of sorghum. The results of this study are essential to farmers and extension officers as a guide to ensure timely fertiliser application to ensure optimum utilisation of nutrients during crop growth.

Keywords: Crop production, nutrient uptake, soil fertility, *Sorghum bicolor* (L.) Moench.

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is an important drought-tolerant crop grown for human consumption in the world (Mwadalu and Mwangi, 2013; Akram *et al.*, 2007). In Kenya, the 'Gadam' variety was introduced to improve farmer food security and income with its high yields (Mwadalu *et al.*, 2022). However, its production is less than the demand due to high mineral fertiliser prices causing inadequate nutrient replenishment and soil fertility decline from nutrient losses (Kavoi *et al.*, 2013;

[1] Kenyatta University, School of Agriculture and Enterprise Development, Nairobi, Kenya
[2] Kenya Forestry Research Institute, Central Highlands Eco Region Research Programme, Nairobi, Kenya

Mwadalu and Mwangi, 2013). Balancing nutrient inputs and removal by crops is thus paramount for reducing nutrient build-up in the soil, thereby addressing environmental concerns and lowering soil fertility management costs (Ngugi *et al.*, 2022).

Nutrient uptake by crops is influenced by soil moisture, aeration, soil temperature and nutrient imbalances (CFI, 1998; Nyawade *et al.*, 2020). Optimum nutrient uptake occurs preceding maximum growth rates (Jones *et al.*, 2015; Ochieng' *et al.*, 2021). Proper timing of nutrient application and application of optimal fertiliser rates is critical for ensuring nutrients are available before peak crop nutrient demand, especially for nitrogen, which is the most limiting factor in most farming systems (Sanchez and Doerge, 1999; Gitari *et al.*, 2018; Jalpa *et al.*, 2020). This study sought to evaluate sorghum N apparent efficiency, assess the effect of N and P fertiliser application on sorghum N uptake and estimate N and P dynamics in the soil.

MATERIALS AND METHODS

Study sites

This study was undertaken in two sites situated in Makueni (KYM) and Machakos (KAT) Counties in Kenya as shown in *Fig. 1*. The two counties are located in the semi-arid parts of Eastern Kenya and have high poverty indices of 60% (Maguta *et al.*, 2021). Makueni County is located between latitudes 1°35' and 2°59' South and longitude 37°10' and 38°30' East, while Machakos County is located between latitudes 0°45´S to 1°31´S and longitudes 36°45´ E to 37°45´E (KNBS, 2019). The two counties lie at altitudes between 1000 and 1600 m above sea level and are characterised by erratic and inadequate rainfall. The dominant soil types in the two counties are Acrisols and Oxisols (Muchena, 1975; FAO/UNESCO, 1970).

Experimental design and setup

The study was laid out using a randomised complete block design. Sorghum, the 'Gadam' variety (sourced from KARI Katumani), was the tested genotype. The study evaluated two factors (phosphorus and nitrogen) each at two levels (0 and 75 kg ha $^{-1}$) resulting in four cross-combined treatments which were replicated thrice. The experiments were undertaken during the short rainy season between October 2012 and March 2013. Each plot measured 4.5 m by 4.5 m with sorghum spacing of 20 cm within rows and 75 cm between rows resulting in 6.67 plants/m^2. At planting, triple superphosphate was applied in each planting hole. The top dressing was undertaken 28 days after planting (DAP) using calcium ammonium nitrate.

Soil characterization and plant tissue analysis

Soil sampling (0–20cm depth) and analysis were undertaken periodically: before experiment establishment, at the seedling stage (30 DAP), at the heading stage (60 DAP) and at sorghum maturity (90 DAP) using standard procedures as described by Savoy (2009) and Okalebo *et al.* (2002). Quantified soil parameters at the onset of the experiment were total nitrogen (N) and carbon (C), pH, available phosphorus (P), magnesium (Mg), extractable potassium (K), calcium (Ca), sodium (Na) and population of bacteria and fungi. Thereafter, only N and P dynamics were observed. Phosphorus extraction was done using Mehlich 1 extraction method. Total N in plant tissues was determined using the flash combustion method as described by Krotz *et al.* (2013).

Determination of nitrogen uptake

Determination of nitrogen uptake based on sorghum grain was calculated using equation [1] as described by Sigua *et al.* (2018):

$$NUG = CTN_g * GY \qquad [1]$$

where CTN_g is the concentration of N (%) in grain and GY is the grain yield (kg ha^{-1}).

Determination of Nitrogen Apparent Efficiency

The apparent nitrogen efficiency (APR) of sorghum was calculated using equation [2] as described by Jalpa *et al.* (2020):

$$APR\ (\%) = \frac{(Nf - Nuf)}{Na} * 10 \qquad [2]$$

where *Nf* and *Nuf* are N accumulation in sorghum grain in kg ha^{-1} in fertilised and unfertilised plots, respectively, while *Na* is the amount of N fertiliser applied (kg ha^{-1}).

Statistical analysis

Data obtained from the study were analysed using R software (version 4.1.0 for windows). Analysis of variance (ANOVA) was conducted at a 95% confidence level to test the causal effect of the various treatments; Pearson correlation and regression analysis were also conducted to assess the presence of relationships between variables and determine the strength of the existing relationships between variables.

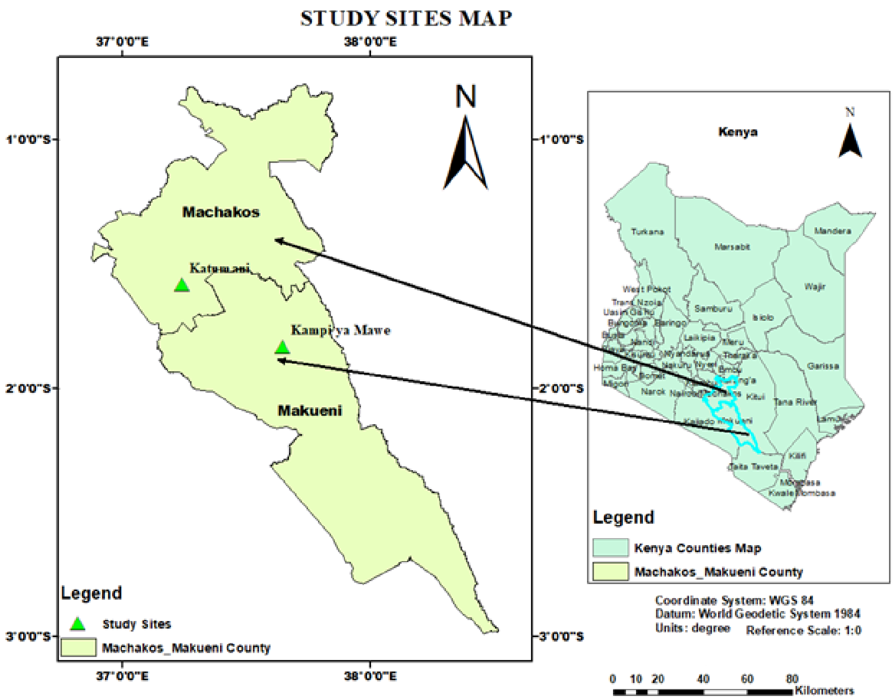

Figure 1 - Map showing study sites

RESULTS AND DISCUSSION

Initial soil chemical characteristics

The initial soil analysis shows that pH ranged from slightly to strongly acidic (6.17 at KAT and 4.88 at KYM). Organic carbon in both sites was extremely low and ranged between 0.3 at KAT and 0.89% at KYM against the optimal range of

2.7%.

Similarly, the soils had low nitrogen (< 0.09%), magnesium (< 30.6 ppm), calcium (< 48.0 ppm) and potassium (< 66.2 ppm). The Katumani site had low phosphorus (< 12.0 ppm) compared to Kampi ya Mawe at 24.6 ppm.

Effect of nitrogen and phosphorus fertilizer on N content in sorghum tissues

Nitrogen contents in sorghum tissues at Kampi ya Mawe were higher at the seedling stage than in the other two growth stages (heading and maturity) concerning the various treatments applied. At the seedling stage, there were significant differences in N content in sorghum tissues after the application of N, P and its combination ($f(3,8) = 8.87; p < 0.006$) - *Fig. 2*. Application of N, P and their combination did not result in substantial variation in N content in sorghum tissues at both heading and maturity stages ($p < 0.14$ and $p < 0.38$, respectively). Nitrogen content in sorghum tissues was higher in plots treated with sole N fertiliser than those treated with a combination of N and P fertiliser (*Fig. 2*). There was an increase in N content in sorghum tissues of 24% in comparison with the untreated control following the application of N at 75 kg ha^{-1}. The combination of N and P fertiliser did not lead to significant increase of N content in sorghum tissues in comparison with the control; a difference of only 10% was observed. Generally, N content in sorghum tissues declined from the seedling to the heading stage; however, there was a slight increase in N content in sorghum grain at the maturity stage in comparison to the heading stage; where an insignificant increase of 8.2% was observed following a coupled application of N and P at 75 kg ha^{-1}. At Kampi ya Mawe, N content in sorghum tissues declined from 4% at the seedling stage to 3% at the maturity stage in plots amended with 75 kg N ha^{-1}; this was a decline of 31%. The untreated control had the least N content in sorghum tissues throughout the growth stages (*Fig. 2*). Sole P application did not affect N content in sorghum tissues.

At Katumani, N content in sorghum tissues differed significantly ($p < 0.05$) (*Fig. 3*). Plots amended with N and P at 75 kg ha^{-1} resulted in the highest N content in sorghum tissues at the 3 sorghum development stages assessed. At the seedling stage, an increase of 19% was observed with the combination of N and P application in comparison with the unamended treatment. Sole N application led to an increase in N content in sorghum tissues of 18% at the seedling stage. At the sorghum maturity stage, N content in the grain was higher in plots amended with N and P; this was an increase of 25% compared with the unamended treatment. Generally, N content in sorghum tissues declined across the three sorghum development stages assessed. A decline of up to 11% was observed with the sole N treatment. The unamended control recorded the lowest sorghum N content across the growth stages.

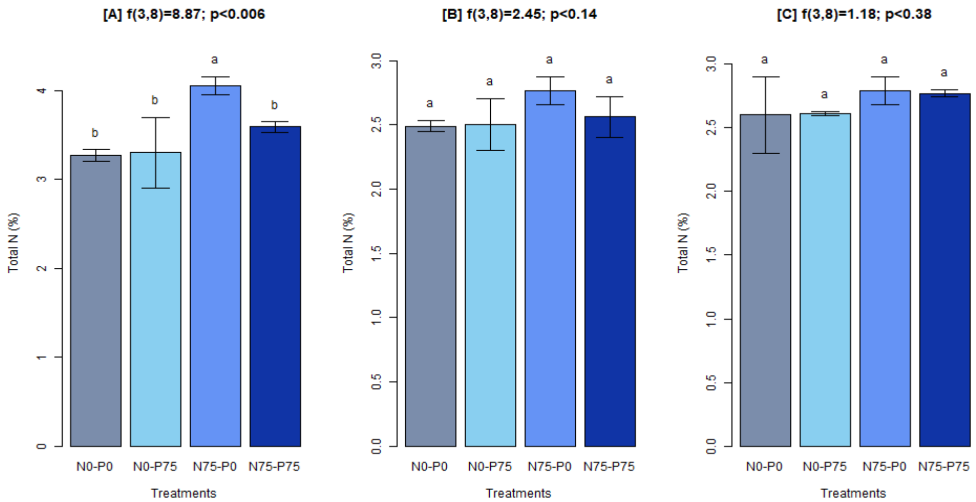

Figure 2 - N content (%) in sorghum tissues at Kampi ya Mawe during 2012/13 short rainy season

Note: Means followed by the same letter in each graph are not significantly different at p<0.05; **(A)** whole plant tissues were analysed at the seedling stage; **(B)** flag leaf tissues were analysed at the heading stage; **(C)** sorghum grains were analysed at sorghum maturity

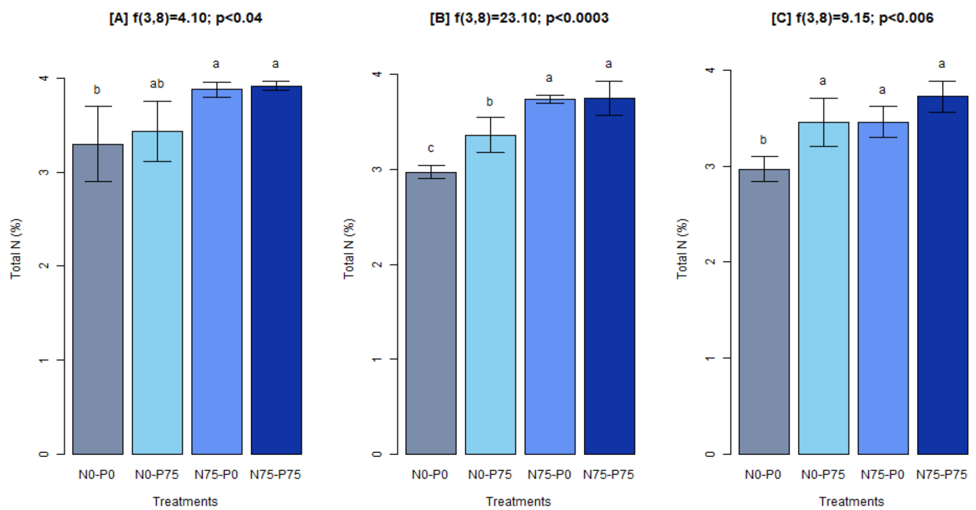

Figure 3 - N content (%) in sorghum tissues at Katumani during 2012/13 short rainy season

Note: Means followed by the same letter in each graph are not significantly different at p<0; **(A)** whole plant tissues were analysed at the seedling stage; **(B)** flag leaf tissues were analysed at the heading stage; **(C)** sorghum grains were analysed at sorghum maturity

In terms of N uptake based on sorghum grains, the current study shows that the control recorded the lowest N uptake in both sites as shown in *Table 1*. Kampi ya Mawe recorded higher N uptake in comparison with the Katumani site. Nitrogen application at 75 kg N ha^{-1} enhanced N uptake in both sites (*Table 1*).

An increase in N uptake of 84.5% and 91.5% in respective KYM and KAT was observed after the application of 75 kg N ha^{-1} in comparison with the unamended control. Kampi ya Mawe recorded a 17.7% higher N uptake than the Katumani site during the growing season. The nitrogen apparent efficiency was higher at KYM (60.4%) than KAT (53.5%) as shown in Table 1 after the application of N fertiliser at 75 kg ha^{-1}.

The higher N content observed at the seedling developmental stage in comparison with the heading stage was probably a result of low biomass accumulation. The decline in N content at the heading stage could be attributed to the dilution effect resulting from high biomass accumulation. Sorghum grain at KYM recorded relatively higher N contents than the N contents observed at the heading stage. This trend could have been the result of N accumulation in sorghum grain tissue. Malathesh (2005) observed comparable findings. A study by Pal *et al.* (1982) further observed a decline in N concentration in whole plant tissues with age up to 75 DAP which was then followed by enhanced N concentration up to maturity. Low moisture content, which affects nutrient uptake, could have led to the low N content in sorghum grain at Katumani (Sigua *et al.*, 2018).

Crop nutrient uptake is influenced by climatic conditions and soil characteristics (Sigua *et al.*, 2018). Inadequate soil moisture and poor aeration resulting from compaction and nutrient imbalances may restrict nutrient uptake, thereby hampering crop growth and development (CF1, 1998; Jones *et al.*, 2015; Nyawade *et al.*, 2019). Low soil moisture could explain the reduced N uptake in Katumani as compared to the Kampi ya Mawe site during the study period. Low soil moisture affects plants' ability to absorb nutrients thus hindering nutrient uptake (Jones *et al.*, 2015; Sigua *et al.*, 2018).

Nutrient uptake by crops is also influenced by the growth stages of the crop as observed in this study. Jones *et al.* (2015) observed increased nutrient uptake during stages of maximum crop growth, which necessitates proper nutrient management to avoid nutrient losses through leaching during low nutrient demand.

Table 1 - Sorghum nutrient uptake based on sorghum grain yield

N application rate	Total N in grain (%)	Sorghum grain yield (kg ha^{-1})	Nutrient uptake based on the grain (kg ha^{-1})	APR (%)
0 kg N ha^{-1} (KYM)	2.60	2059.62	53.55	-
75 kg N ha^{-1} (KYM)	2.79	3542.01	98.82	60.4
0 kg N ha^{-1} (KAT)	2.97	1476.85	43.86	-
75 kg N ha^{-1} (KAT)	3.72	2257.45	83.98	53.5

Note: KYM = Kampi ya Mawe; KAT = Katumani

Jones and Jacobsen (2002) and Nduwimana *et al.* (2020) further noted that nutrient uptake was influenced by nutrient concentration in the soil and roots' ability to absorb these nutrients. This trend explains the enhanced N uptake following the application of higher N doses at the two sites. Similar findings on increased N uptake following application of higher N doses were reported by Abunyewa *et al.* (2017) and Ochieng' *et al.* (2021) where foliage N uptake increased by up to 18% after N application in comparison with the control while grain N content increased by 12% upon N application.

Previous studies reported that crops utilise only 50% of N applied thus the need for balancing nutrient application with nutrient uptake (Worland *et al.*, 2017). Sigua *et al.* (2018) reported sorghum nitrogen apparent efficiency of 60.5% and 57.1% with the application of 85 and 170 kg N ha^{-1}, respectively. The information on nitrogen apparent efficiency is crucial for determining the efficiency of current management practices in terms of the rate and timing of N fertiliser applications (Jalpa *et al.*, 2020). The nitrogen apparent efficiency is influenced by soil moisture availability and N application rate (Sigua *et al.*, 2018). Nitrogen uptake and efficient utilisation are crucial to the N economy and yield improvement in agricultural systems (Zhong *et al.*, 2014; Gitari *et al.*, 2018; Sigua *et al.*, 2018).

Effect of N and P fertiliser application on nitrogen dynamics in soil

Tables 2 and *3* show the concentration of available nitrogen (NO3- N) in the soil during the growing period of sorghum as influenced by N and P fertiliser application. Significant differences were observed in nitrate concentrations at all the growth stages (30–90 DAP) at both sites ($p < 0.001$). In Kampi ya Mawe (*Table 2*), nitrate concentration increased substantially upon N application; however, it declined progressively throughout the growth period, with the lowest concentrations recorded at the harvest stage in both sites. An increase in NO_3^-N of 53% was observed sole N application at 30 DAP in comparison with the control. Integration of N and P enhanced NO_3^-N by 70% in comparison with the control at the seedling stage. Sole P application enhanced NO_3^-N by 16% during the same period.

The concentration of NO_3^-N at 60 DAP in plots treated solely with N fertiliser was 76% higher than the unamended treatment, whereas the integration of N and P at this stage led to an increase in NO_3^-N of 41%. Sole P application on the other hand resulted in a decline in NO_3^-N of 26.9%. At the harvesting stage, the concentration of NO_3^-N in sole N plots was 81% higher than the control with sole P application and integration of N and P recording lower concentration than the control (*Table 2*).

At Katumani, there were significant differences in NO_3^-N ($p < 0.001$) at all growth stages (*Table 3*). Generally, NO_3^-N in the soil declined gradually throughout the growing season. At 30 DAP, the sole application of N fertiliser resulted in a 116% increase in NO_3^-N in comparison with the control, while the integration of N and P fertiliser enhanced NO_3^-N by 165% compared to the unamended treatment. However, sole P application resulted in a decline of

NO_3^-N of 27% during the same period. At 60 DAP, the sole N application yielded the highest NO_3^-N in the soil, 105% higher than the control. The combined application of N and P resulted in an increase in NO_3^-N of 63% in comparison with the unamended treatment. Sole application of P led to a decline in NO_3^-N in the soil by 33% compared to the control treatment. Similar trends were observed at 90 DAP, where sole N application resulted in the highest NO_3^-N in the soil, 111% higher than the control. Combined application of N and P enhanced NO3- N in the soil by 74%, while sole P application led to a decline in NO_3^-N of 21% in comparison with the unamended control.

The higher NO_3^-N reported in this study following the application of sole N fertiliser and integration of N and P could be attributed to N addition from the fertiliser itself. Liu *et al.* (2020), similarly reported that NO_3^-N in the soil was enhanced following N application at different rates; an increase of up to 133% was recorded with NP application in comparison with the control. The decrease in NO_3^-N across the sorghum growth stages could be attributed to nitrate uptake by sorghum plants (Horner, 2008) and the leaching of nitrates throughout the growing season (Zeeshar *et al.*, 2015; Li *et al.*, 2019; Pasley *et al.*, 2020). A similar trend of reduced NO_3^-N following sole P application was also reported by Akram *et al.* (2015); this could be attributed to enhanced NO_3^-N uptake by sorghum resulting from increased root growth.

Table 2 - Concentration of soil nitrate N (mg/kg) at Kampi ya Mawe during 2012/13 short rainy season

Treatment	30 DAP	60 DAP	90 DAP
N0-P0	6.37±0.24b	3.12±0.11c	1.39±0.03d
N0-P75	7.38±0.36b	2.28±0.02d	0.74±0.29c
N75-P0	9.73±0.80a	5.49±0.15a	2.51±0.11a
N75-P75	10.85±1.01a	4.39±0.17b	1.38±0.03b
f(3,8)	27.68	360.3	70.38
P value	0.001	0.001	0.001

Note: Means followed by the same letter along the column are not significantly different at p < 0.05; DAP = days after planting

Table 3: Concentration of soil nitrate N (mg/kg) at Katumani during 2012/13 short rainy season

Treatment	30 DAP	60 DAP	90 DAP
N0-P0	10.57±1.01c	9.55±0.21c	7.11±0.12c
N0-P75	7.67±0.03d	6.44±0.58d	5.65±0.02d
N75-P0	22.95±0.03b	19.10±0.90a	15.01±0.13a
N75-P75	27.99±2.01a	15.56±0.21b	12.37±0.12b
f(3,8)	221.86	318.3	5031.14
P value	0.001	0.001	0.001

Note: Means followed by the same letter along the column are not significantly different at p < 0.05; DAP = days after planting

Phosphorus plays a crucial role in root growth and development, which have necessary functions in nutrient uptake by crops (Horner, 2008; Gitari *et al.*, 2020). Maintaining a positive N balance is essential due to the key role played by nitrogen in photosynthesis that regulates crop growth and development (Liu *et al.*, 2014; Nasar *et al.*, 2021). To ensure optimal utilisation of N fertiliser applied and reduce N leaching, Momesso *et al.* (2021) recommended split application of N fertiliser to ensure application coincides with crop N demand.

Effect of N and P application on available P dynamics in soil

Tables 4 and *Table 5* show available P levels in the soil during the growing season of sorghum as influenced by N and P application. There were significant differences in available P in the soil from 30 DAP to 90 DAP in the two sites ($p<0.001$) (*Table 4* and *Table 5*).

P concentration in the soil increased with increased P application. Generally, available P declined throughout the sorghum growth period from 30 DAP to 90 DAP. At 30 DAP in Kampi ya Mawe, the combined application of N and P resulted in the highest available P, which was 161.5% higher than the control treatment. Sole P application recorded available P, which was 95.1% higher than the unamended control. Sole N application enhanced available P by 35.5% in comparison with the control. At 60 DAP, sole application of P yielded the highest available P, 94.8% higher than the control as shown in *Table 4*.

Table 4 - Concentration of soil available P (mg/kg) at Kampi ya Mawe during 2012/13 short rains

Treatment	30 DAP	60 DAP	90 DAP
N0-P0	21.03±1.45d	19.40±0.40c	16.79±0.04d
N0-P75	41.10±0.20b	37.80±2.30a	28.50±2.40b
N75-P0	28.50±0.60c	27.37±1.00b	25.50±1.80c
N75-P75	55.00±1.01a	37.60±1.20a	36.10±0.80a
f(3,8)	756.7	119.9	79.3
P value	0.001	0.001	0.001

Note: Means followed by the same letter along the column are not significantly different at p < 0.05; DAP = days after planting

Table 5 - Concentration of soil available P (mg/kg) at Katumani during 2012/13 short rainy season

Treatment	30 DAP	60 DAP	90 DAP
N0-P0	11.00±0.15d	9.40±0.50d	9.23±0.55d
N0-P75	40.17±1.05b	33.60±0.50b	27.20±0.10b
N75-P0	29.40±0.40c	28.30±1.40c	22.60±2.10c
N75-P75	45.20±1.30a	38.30±0.80a	37.10±2.40a
f(3,8)	528.5	622.0	153.3
P value	0.001	0.001	0.001

Note: Means followed by the same letter along the column are not significantly different at p < 0.05; DAP = days after planting

The combined application of N and P enhanced available P by 93.8% in comparison with unamended treatment. Sole N application on the other hand enhanced available P by 41.1%. Available P at 90 DAP was higher in plots ameliorated with N and P; this treatment enhanced available P by 115% in comparison with the control. Sole P application led to an increase in available P of 69.7% while sole N application increased available P by 51.9% in comparison with the control treatment.

In Katumani, available P concentration differed significantly across treatments in all the assessment periods (*Table 5*). At 30 DAP, the combined application of N and P at 75 kg ha^{-1} yielded the highest available soil P, 310.9% higher than the unamended control. Sole P application (N0-P75) enhanced soil available P by 265.2% while sole N application increased available P by 167.2% in comparison with the control treatment. At 60 DAP, there was an increase in available P following NP application of 307.4% and 257.4% following sole P application. Plots ameliorated solely with N recorded 201.1% higher available P than the control. At 90 DAP, plots treated with NP recorded the highest available P, which was 302% higher than the unamended control. The sole P application yielded 194.7% higher available N than the control, while the sole N application enhanced available P by 144.9%. The control recorded the lowest available P across the assessment periods.

The high available P in plots ameliorated with P and NP could be attributed to P addition through the fertiliser applied. In this study, the combined application of P and N resulted in the highest soil available P in both sites. This could be attributed to the lowering of soil pH following the application of ammonium-based N fertiliser (calcium ammonium nitrate). Horner (2008) reported that N addition enhanced P availability in the soil; the study attributed this to the influence of N on rhizosphere pH. The application of N aids in the mineralisation of P, thereby making it available for plant uptake. The decline in available P across the assessment period can be attributed to sorghum uptake since P immobility hinders leaching (Penn State Extension, 2017). The concentration of available P remained relatively high throughout the growing period, and this can be attributed to low soil moisture due to depressed rainfall during the experiment period, which could have lowered P uptake by sorghum and reduced P losses from runoff (Horner, 2008; Seleiman *et al.*, 2022).

Relationship between available N concentration and sorghum N uptake

The present study shows a significant positive linear relationship between NO_3^- N in the soil and N content in sorghum tissues in Kampi ya Mawe and Katumani sites (*Fig. 4* and *Fig. 5*). At Kampi ya Mawe, a significant positive relationship was recorded at the seedling stage ($p < 0.05$; r = 0.64). This means that 40% of variation observed made in sorghum N content can be attributed to NO_3^- N in the soil. At the heading stage, a significant positive linear relationship ($p < 0.05$; r = 0.66) was observed between NO_3^- N concentration in the soil and N content in sorghum tissues; 44% of variations recorded in sorghum N content can be attributed to the variation of NO_3^- N in the soil (Figure 4).

At Katumani, a significant positive relationship was recorded at the seedling stage ($p < 0.01$; r = 0.75). This means that 56% of variation observed made for sorghum N content can be attributed to NO_3^-N in the soil. At the heading stage, a significant positive linear relationship ($p < 0.01$; r = 0.70) was observed between NO_3^-N in the soil and N content in sorghum tissues; therefore 48% of variation recorded in sorghum N content can be attributed to the variation of NO_3^- N in the soil (*Fig. 5*).

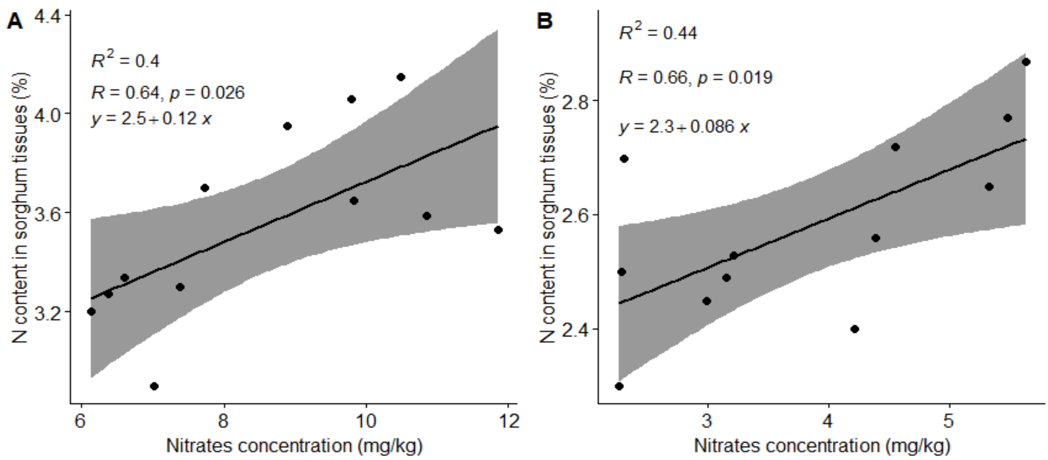

Figure 4 - Relationship between N concentration and sorghum N uptake at two growth stages at Kampi ya Mawe; seedling stage; (B) sorghum heading stage

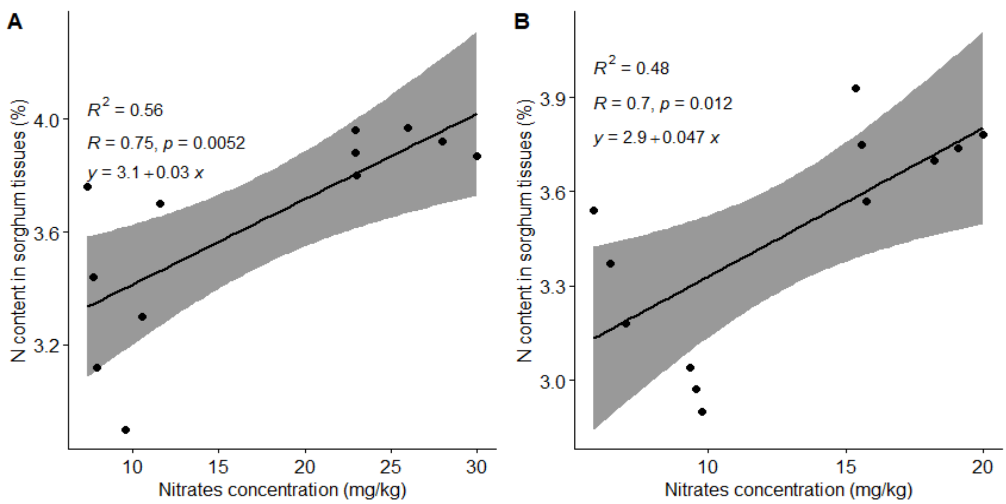

Figure 5 - Relationship between N concentration and sorghum N uptake at two growth stages at Katumani; (A) seedling stage and (B) sorghum heading stage

The present study thus shows that an increase in NO_3^- N concentration in the soil resulted in enhanced N content in sorghum tissues at the seedling and heading stages of sorghum growth. The NO_3^-N in the soil resulted from N application through CAN fertiliser.

Similar trends were observed by Chen *et al.* (2018), Niu *et al.* (2020) and Faridvand *et al.* (2021), where N fertilisation enhanced foliar N concentration thus stimulating photosynthetic activity, which eventually led to improved biomass accumulation. Cassman *et al.* (2002) reported that crop physiological N requirement is controlled by the efficiency of the plant to convert N into biomass and grain yield. Understanding N uptake is crucial to ensure optimal benefits resulting from the proper timing of N fertiliser application and minimise losses through leaching and other pathways.

CONCLUSIONS AND RECOMMENDATIONS

The present study shows that N application enhanced both available N in the soil and N content in sorghum tissues. The study further revealed that increasing N application rates enhanced N uptake by the sorghum in the two study sites. Available N and P declined across the sorghum growth stages; this can be attributed to uptake by the test crop (sorghum). A positive linear relationship was also observed between NO_3^- N concentration in the soil and N content in sorghum tissues. Nitrogen apparent efficiency was higher at KYM than at KAT, which could have been influenced by differences in soil moisture between the two sites during the growth period. The current study further revealed that N uptake by sorghum differed in each sorghum developmental stage. The study recommends that N application be done in splits to ensure availability during maximum crop demand and minimise losses through leaching. Further studies are recommended to evaluate the N recovery of different sorghum varieties being promoted in the country grown using different N fertiliser rates.

Authors contributions

RM, study conceptualisation, data collection, analysis and manuscript development; BM, MM and HG, data collection and manuscript development.

Funding statement

The authors would wish to express their gratitude to the Alliance for a Green Revolution in Africa (AGRA) for funding the research through the 2012–2014 Kenyatta University soil health programme.

REFERENCES

Abunyewa, A.A., Wortmann, C.S. and Mason, S.C. (2017). Grain sorghum nitrogen use as affected by planting practise and nitrogen rate. *Journal of Soil science and plant nutrition*, *1*, http://dx.doi.org/10.4067/S0718-95162017005000012.

Akram, A., Fatima, M., Ali, S., Jilani, G. and Asghar, R. (2007). Growth, yield and nutrient uptake of sorghum in response to integrated phosphorus and potassium management. *Pakistan Journal of Botany*, 39(4), 1083-1087.

Akram, Z., Hussain, S., Afzal, M., Waquar, A. and Farooq, M.U. (2015). Nitrate status of soil in areas where high doses of nitrogen are being applied. *Applied*

Science Reports, 12(2), 98-100, http://dx.doi.org/10.15192/PSCP/ASR.2015.12.2.98100.

CFI (Canadian Fertilizer Institute) (1998). Nutrient uptake and removal by field crops. Eastern Canada.

Cassman, K.G., Dobermann, A.R., Walters, D.T., (2002). Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. *Agronomy & Horticulture - Faculty Publications*. 356. http://digitalcommons.unl.edu/agronomyfacpub/356.

Chen, J., Dong, C., Yao, X., Wang, W. (2018). Effects of nitrogen addition on plant biomass and tissue elemental content in different degradation stages of temperate steppe in northern China. *Journal of Plant Ecology*, 1–10, https://doi.org/10.1093/jpe/rtx035.

FAO/ UNESCO (1970). Soil map of the world, Volume 1. Paris: UNESCO.

Faridvand, S., Rezaei-Chiyaneh, E., Battaglia, M., Gitari, H., Raza, M.A., and Siddique, K.H.M. (2021). Application of bio and chemical fertilizers improves yield, and essential oil quantity and quality of Moldavian balm (*Dracocephalum moldavica* L.) intercropped with mung bean (*Vigna radiata* L.). *Food and Energy Security*. 11, e319, https://doi.org/10.1002/fes3.319.

Horner, E.R. (2008). The effect of nitrogen application timing on plant available phosphorus (Master of Science thesis, The State University of Ohio, USA.

Gitari, H.I., Karanja, N.N., Gachene, C.K.K., Kamau, S., Sharma, K., and Schulte-Geldermann, E. (2018). Nitrogen and phosphorous uptake by potato (*Solanum tuberosum* L.) and their use efficiency under potato-legume intercropping systems. *Field Crops Resource*, 222, 78-84, https://doi.org/10.1016/j.fcr.2018.03.019.

Gitari, H.I., Shadrack, N., Kamau, S., Gachene, C.K.K., Karanja, N.N., and Schulte-Geldermann, E. (2020). Agronomic assessment of phosphorus efficacy for potato (*Solanum tuberosum* L) under legume intercrops. *Journal of Plant Nutrition,* 43, 864-878. https://doi.org/10.1080/01904167.2019.1702202.

Jalpa, L., Mylavarapu, R.S., Hochmuth, G.J., Wright, A.L., van Santen, E. (2020). Apparent Recovery and Efficiency of Nitrogen Fertilization in Tomato Grown on Sandy Soils, *HortTechnology*, 30(2), 204-211, https://doi.org/10.21273/HORTTECH04480-19

Jones, C., and Jacobsen, J.S. (2002). Nutrient Management Module No. 2, Plant Nutrition and Soil Fertility. Montana State University. https://www.semanticscholar.org.

Jones, C., Dinkins, C.P. and Olson-Rutz, K. (2015). Nutrient uptake timing by crops: to assist with fertilizing decisions. Montana State University. https://landresources.montana.edu.

Kavoi, J., Kisilu, R., Kamau, G, Wafula, J., Njangungi N., and Nganga, T. (2013). Gadam sorghum production and marketing through a public private partnership in Eastern Kenya, KARI Nairobi, Kenya - 39pp.

KNBS (Kenya National Bureau of Statistics) (2019). Kenya population and housing census results. www.knbs.or.ke.

Krotz, L. Ragaglia, L., and Giazzi, G. (2013). Quick, accurate nitrogen, total Carbon and total Organic carbon determination in soils by elemental analysis, Strada, Rivoltana, Italy.

Liu, B., Wu, J., Yang, S., Schiefelbein, J. and Gan, Y., (2020). Nitrate regulation of lateral root and root hair development in plants, *Journal of Experimental Botany*, 71(15), 4405-4414, https://doi.org/10.1093/jxb/erz536.

Liu, C. W., Sung, Y., Chen, B. C., & Lai, H. Y. (2014). Effects of nitrogen fertilizers on the growth and nitrate content of lettuce (Lactuca sativa L.*). International journal of environmental research and public health*, 11(4), 4427-4440, https://doi.org/10.3390/ijerph110404427.

Maguta, J.K., Nzengya, D.M., Mutisya, C., Wairimu, J. (2021). Building Capacity to Cope with Climate Change-Induced Resource-Based Conflicts Among Grassroots Communities in Kenya. In: Oguge, N., Ayal, D., Adeleke, L., da Silva, I. (eds) African Handbook of Climate Change Adaptation. Springer, Cham. https://doi.org/10.1007/978-3-030-45106-6_131

Malathesh, G.H. (2005). Nutrient Substitution through Organics in Maize (Master's Thesis), University of Agricultural Sciences, Dhār ward.

Momesso, L., Crusciol, C.A.C., Soratto, R.P., Nascimento, C.A.C., Rosolem, C.A., Moretti, L.G., Kuramae, E.E., Cantarella, H. (2021). Early nitrogen supply as an alternative management for a cover crop-maize sequence under a no-till system. *Nutrient Cycling in Agroecosystems*, 121, 1-14 https://doi.org/10.1007/s10705-021-10158-1.

Muchena, F.N. (1975). Soils of Kampi ya Mawe: Agricultural experimental sub-station. Detailed soil survey report no. D1 1975.

Mwadalu, R., Mwangi, M. (2013). The potential role of sorghum in enhancing food security in semi-arid Eastern Kenya: A review. *Journal of Applied Biosciences*, 71, https://doi.org/10.4314/jab.v71i1.98826

Mwadalu, R., Mochoge, B., Mwangi, M., Maitra, S. and Gitari, H. (2022). Response of Gadam sorghum (*Sorghum bicolor*) to farmyard manure and inorganic fertilizer application. *International Journal of Agriculture, Environment, and Biotechnology*. 15(1), 51–60, https://doi.org/10.30954/0974-1712.01.2022.6.

Nasar, J., Khan, W., Khan, M.Z., Gitari, H.I., Gbolayori, J.F., Moussa, A.A., Mandozai, A., Rizwan, N., Anwari, G., and Maroof, S.M. (2021). Photosynthetic activities and photosynthetic nitrogen use efficiency of maize crop under different planting patterns and nitrogen fertilization. *Journal of Soil Science and Plant Nutrition,* 21, 2274–2284, https://doi.org/10.1007/s42729-021-00520-1.

Nduwimana, D., Mochoge, B., Danga, B., Masso, C., Maitra, S., and Gitari, H (2020). Optimizing nitrogen use efficiency and maize yield under varying fertilizer rates in Kenya. *International Journal of Bioresource Science,* 7(2), 63-73, https://doi.org/10.30954/2347-9655.02.2020.4.

Ngugi, M.M., Gitari, H.I., Muui, C.W., Gweyi-Onyango, J.P. (2022). Growth tolerance, concentration, and uptake of heavy metals as ameliorated by silicon application in vegetables. *International Journal of Phytoremediation,* https://doi.org/10.1080/15226514.2022.2045251.

Niu, J., Lu, T., Lin, Y., & Zhang, W. (2020). Effects of nitrogen addition on the characteristics of foliar and soil ecological stoichiometry in Xishuangbanna tropical rainforest, Southwest China. *Journal of Tropical Forest Science*, 32, 1-7, https://doi.org/10.26525/jtfs32.1.1

Nyawade, S.O., Gachene, C.K.K., Karanja, N.N., Gitari, H.I., Schulte-Geldermann, E. (2019). Controlling soil erosion in smallholder potato farming systems using legume intercrops. *Geoderma Regional*, 17 e00225, https://doi.org/10.1016/j.geodrs.2019.e00225.

Nyawade, S.O., Karanja, N.N., Gachene, C.K.K., Gitari, H.I., Schulte-Geldermann, E., Parker, M. (2020). Optimizing soil nitrogen balance in a potato cropping system through legume intercropping. *Nutrient Cycling in Agroecosystems*, 117, 43–59. https://doi.org/10.1007/s10705-020-10054-0.

Ochieng', I.O., Gitari, H.I., Mochoge, B., Rezaei-Chiyaneh, E., Gweyi-Onyango, J.P. (2021). Optimizing maize yield, nitrogen efficacy and grain protein content under different N forms and rates. *Journal of Soil Science and Plant Nutrition*, 21(3), 1867–1880, https://doi.org/10.1007/s42729-021-00486-0.

Okalebo, J.R., Kenneth, W.G. and Woomer, P.L. (2002). Laboratory method of soil and plant analysis. Second edition, SACRED Office Nairobi, 128p.

Pal, U.R., Upadhyay, Singh, S.P., Umrani, N.K. (1982). Mineral nutrition and fertilizer response of grain sorghum in India- A review of 25 years. *Fertilizer Research*, 3, 141–159, https://doi.org/10.1007/BF01082974.

Pasley, H. R., Camberato, J. J., Cairns, J. E., Zaman-Allah, M., Das, B., Vyn, T. J. (2020). Nitrogen rate impacts on tropical maize nitrogen use efficiency and soil nitrogen depletion in eastern and southern Africa. *Nutrient cycling in agroecosystems*, 116(3), 397-408, https://doi.org/10.1007/s10705-020-10049-x.

Penn State Extension (2017). Managing Phosphorus for crop production. Agronomy facts 13. College of Agricultural Sciences, Penn State University. https://extension.psu.edu/managing-phosphorus-for-crop-production.

Sanchez, C.A., Doerge, T.A. (1999). Using nutrient uptake patterns to develop efficient management strategies for vegetables. Horticulture Technology 9(4): The University of Arizona.

Savoy, H. (2009). Interpreting Mehlich 1 and 3 soil test extractant results for P and K in Tennessee, University of Tennessee, Institute of Agriculture.

Seleiman, M.F., Aslam, M.T., Alhammad, B.A., Hassan, M.U., Maqbool, R., Chattha, M.U., Khan, I., Gitari, H.I., Uslu, O.S., Roy, R., Battaglia, M.L. (2022). Salinity Stress in Wheat: Effects, Mechanisms and Management Strategies. *Phyton-International Journal of Experimental Botany*, 91(4), 667-694, https://doi.org/10.32604/phyton.2022.017365.

Sigua, G.C., Stone, K.C., Bauer, P.J. and Szogi, A.A. (2018). Biomass and nitrogen use efficiency of grain sorghum with nitrogeb and supplementl iirigation. *Agronomy journal*, 110(3), 1119-1127, https://doi.org/10.2134/agronj2017.09.0533.

Worland, B., Robinson, N., Jordan, D., Schmidt, S. and Godwin, I. (2017). Post-anthesis nitrate uptake is critical to yield and grain protein content in Sorghum bicolor. *Journal of Plant Physiology*, 216, 118-124, https://doi.org/10.1016/j.jplph.2017.05.026.

Zhong, H., Wang, Q., Zhao, X., Du, Q., Zhao, Y., Wang, X., Jiang, C., Zhao, S., Cao, M., Yu H., Wang, D. (2014). Effects of Different Nitrogen Applications on Soil Physical, Chemical Properties and Yield in Maize (Zea mays L.). *Agricultural Sciences,* 5, 1440-1447, http://dx.doi.org/10.4236/as.2014.514155