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Effect of nitrogen fertilizer on nitrogen use efficiency and yield of selected sorghum genotypes in semi-arid regions of Kenya

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Abstract

Sorghum production in semi-arid lands is constrained by inadequate soil moisture and low nitrogen. Research was carried out in semi-arid Machakos between 2018-2020 to determine the effect of nitrogen fertilizer on nitrogen use efficiency, yield on selected sorghum genotypes and genotypes suitable for low soil fertility in semi-arid lands. The experiment was a randomized complete block design (RCBD) in a split plot arrangement with 11 sorghum genotypes in the main plot and nitrogen (0, 6.5 and 32.5 $kgha^{-1}$) as the sub-plots in three replicates. Nitrogen use efficiency (NUE) and its indices agronomic efficiency (AE), nitrogen internal utilization (IE), physiological efficiency (PE), nitrogen recovery efficiency, nitrogen harvest index (NHI) and partial factor productivity (PFP) were obtained from sorghum yield data and nitrogen uptake. The results showed that nitrogen application at 6.5 $kgha^{-1}$ and 32.5 $kgha^{-1}$ significantly increased grain yield, stover weight and total dry matter (TDM) by 43% and 116%, 39% and 85% and 42% and 57% respectively. Sorghum genotypes TTKKIAMA6, KTIRASTAMMA4, SNYAKTOSA5, and MKNKKIRWMA2 had significantly higher grain yield and low N uptake implying they are N-efficient genotypes. NUE of sorghum decreased with increasing N application. Nitrogen internal utilization efficiency (IE) was significantly higher at zero N application rate implying better N assimilation by sorghum genotypes at low N. AE, PE, RE and PFP were all significantly higher at 6.5 kg N ha^{-1}. All tested genotypes had significantly high NUE (90 to 1148 $kgkg^{-1}$, RE (27 to 94 $kgkg^{-1}$), AE (41 to 139 $kgkg^{-1}$), PE (27 to 84 $kgkg^{-1}$) and IE (41 to 139 $kgkg^{-1}$) than the check (Gadam). It was concluded that sorghum genotypes yield parameters were increased by nitrogen application, NUE was highest at low N levels and its indices were significantly higher at 6.5 kg Nha^{-1}. Four genotypes were found to be highly N-efficient and are recommended for sorghum improvement.

Keywords: *N-efficient sorghum genotypes; nitrogen response; nitrogen use efficiency; Semi-arid lands; sorghum genotypes*

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Introduction

Sorghum production in semi-arid lands is constrained by inadequate soil moisture, soil fertility (Kathuli and Itabari, 2015; Shamme *et al.*, 2016; Workat *et al.*, 2020) and planting of inappropriate genotypes (Omoro, 2013). This has led to a decline in sorghum yields which currently is about 0.5t ha^{-1} in semi-arid lands in Kenya (Muui *et al.* 2019) against a yield potential of 4 - 7 t ha^{-1} (Abunyewa *et al.,* 2017; Queiroz *et al.,* 2018; M'Ragwa, 1996).

The semi-arid lands have low fertility soils, especially low organic carbon (< 1.0%) and nitrogen (< 0.2%) (Queiroz *et al.,* 2018; NAAIAP, 2014; Esilaba *et al.,* 2011; Lal, 2004) due to scarcity of organic materials for decomposition, nitrogen losses through de- nitrification, leaching and volatilization at prevailing high temperatures and soil erosion. Among the macro elements required for crop production in semi-arid lands, nitrogen is very limiting in sorghum growing regions in Kenya (NAAIAP, 2014; Itabari *et al.,* 2013), East Africa (Egeru *et al.,* 2019) and beyond (Queiroz *et al.,* 2018; Lal, 2004) and requires to be applied to soil for increased productivity depending on soil nitrogen status, weather, rainfall amounts, intended yield and nutritional status (Workat *et al.,* 2020; Wang *et al.,* 2014).

Excess application of nitrogen can contribute to environmental pollution or delay sorghum flowering, physiological maturity, and increased crop lodging across sorghum genotypes (Shamme *et al.,* 2016). In semi-arid areas of eastern, coast and western regions of the country, sorghum genotypes are grown with limited inputs (Muui *et al.,* 2019) and attain low yields due to low soil fertility and climate variability. In these areas, farmers grow various sorghum genotypes with limited nitrogen application despite sorghum having huge response to nitrogen application (Buah and Mwinkaara, 2009). Survey conducted in these regions revealed that 44%, 32% and 25% of farmers in Coast, Nyanza and Eastern use no inputs for sorghum production respectively (Muui *et al.,* 2019).

Sorghum genotypes have different nitrogen use efficiency (Mahama, 2012; Mahama *et al.,* 2014) but there is limited information on sorghum genotypes that can survive under low soil fertility conditions with high grain production in the sorghum growing regions in semi-arid Kenya. This calls for determination of sorghum genotypes which can survive in low soil fertility conditions and produce high yields under those conditions. These type of sorghum genotypes are N efficient cultivars (Hirose, 2011; Dobermann, 2007; Moll *et al.,* 1982; Youngquist *et al.,* 1992) and are characterized by high nitrogen use efficiency (NUE).

NUE expresses the ability of a crop to use nitrogen from fertilizer and soil. It is the ratio of plant nitrogen to soil nitrogen (PN/SN) and refers to how much grain of a crop is produced per unit amount of fertilizer nitrogen from fertilizer and soil (Shamme *et al.,* 2016; Moll *et al.,* 1982). It can be expressed as kg grain/kg N (Moll *et al.,* 1982) or kg total dry matter/kg N uptake (Hawkesford *et al.,* 2014; Hirose, 2011). For sorghum it can be as low as 17 to 60 kg grain/kg of nitrogen depending on genotypes and management (Mahama, 2012; Sigua *et al.,* 2018; Ajeigba *et al.,* 2018), rainfall in the season and time of assessment, genotype and variety (Abunyewa *et al.,* 2017; Mahama, 2012) and whether the crop is given supplementary irrigation (Sigua *et al.,* 2018) and amount of soil moisture.

Use of N efficient sorghum cultivars increased the production of sorghum based cropping system in West Africa (Maranville *et al.,* 2002). It would be justified to determine these sorghum genotypes which are efficient in nitrogen use or have high nitrogen use efficiency in semi-arid lands because they will have high yields at low nitrogen application and would reduce cost of fertilizer nitrogen required in sorghum production in low soil fertility status in semi-arid lands.

Since sorghum genotypes have been found to have variable response to nitrogen application (Mahama, 2012; Mahama *et al.,* 2014), it was important to evaluate the nitrogen use efficiency of sorghum genotypes found in the semi-arid lands of Kenya. This would identify genotypes with significantly higher nitrogen use efficiency, low N-uptake and high utilization for higher grain production. This would enhance commercial sorghum growing and food security in low fertile soils situation in semi-arid lands.

The objectives of this research were 1). To determine the effect of nitrogen fertilizer on nitrogen use efficiency of 11 selected sorghum genotypes grown in semi-arid lands in Kenya. 2). to determine the effect of nitrogen fertilizer on yield of selected sorghum genotypes. 3). to identify N-efficient sorghum genotypes grown in semi-arid lands.

Materials and methods

The study site

The research work was conducted at KALRO Katumani, Machakos in short rains of 2018 and 2020. The site lies 1° 35'S and 37° 14'E and at 1600 m above sea level. The mean annual temperatures vary from a minimum and maximum of 13.7°C and 24.7°C respectively (Wamari *et al.,* 2012). Rainfall distribution in Katumani is bimodal with a long rains season from March to May and a short rains season in October to December. The average rainfall for the long rains is 250mm while that of the short rains is 350mm (Wamari *et al.,* 2012) Long rains are very unreliable, poorly distributed and insufficient for crop production (Itabari *et al.,* 2011). The soils are sandy clay loamy and have low in organic matter content, they are prone to surface crusting and vulnerable to erosion due to their weak structural stability of aggregates. The soils are classified as chromic Luvisols due to colour and clay enrichment with depth (FAO/UNESCO, 1990).

Soil sampling and analysis

The soils were sampled at three depths 0-15, 15-30, and 30-60 cm, from the experimental field before planting. Seven to 10 spots were sampled from 0-60 cm depth. Three labeled buckets were used for bulking 0-15cm, 15-30cm and 30-60cm soil samples from the same sampling spot. This was repeated for all 7-10 sampling spots. The soils from different depths were composited and 500g soil resampled for analysis. Three composited samples were taken to University of Nairobi, Kabete campus for analysis using standard methods as outlined by Hinga *et al.,* (1980) for macro and micronutrients and soil reaction. Soil pH was measured in water at 1:2.5 soil water suspension using glass calomel electrode. Organic carbon was determined from oxidizing 0.5g of fine soil with potassium dichromate in presence of concentrated sulphuric acid and heat. Excess chromic acid was titrated against standard ferrous sulphate solution using diphenylamine as indicator. Phosphoric acid was added to form a complex with the ferric iron to provide a sharper colour change of the indicator. Soil total nitrogen (%N) was determined after digesting the soil with concentrated sulphuric acid and selenium mixture as catalyst (5g selenium+ 25g hydrated copper sulphate + 1000g of potassium sulphate). Nitrogen in organic compounds was converted into ammonium sulphate using Kjeldahl digestion procedure (Bremner, 1960). The digest was made alkaline with sodium hydroxide to release ammonia which was distilled into excess 1% boric acid-indicator solution. This forms ammonium borate and excess boric acid was back titrated with 0.1N H_2SO_4 and percent N is calculated.

Available phosphorus, magnesium, calcium, potassium and sodium were extracted from the soil using a mixture of dilute mineral acid (0.1N HCl + 0.025N H_2SO_4). The acid serves to replace the bulk of exchangeable metal cations and the sulphate anion is exchanged for phosphate. Other macro-elements phosphorus and magnesium were determined colorimetrically while calcium, potassium and sodium were determined by flame photometry. Trace elements iron, copper, manganese and zinc were extracted from the soil using 0.1 N HCl solution and determined by atomic absorption spectrometer (AAS). The soil analysis results are shown in Table 1.

Table 1. Soil analysis from the experimental field at KALRO Katumani, Machakos SR 2018.

Soil depth	Acidity	%			Cmol/kg			ppm				
Cm	**pH**	**OC**	**N**	**K**	**Na**	**Ca**	**Mg**	**P**	**Mn**	**Fe**	**Cu**	**Zn**
0-15	6.17	0.88	0.08	2.05	0.5	4.5	1.8	19.7	30.7	76.2	2.1	5.6
15-30	6.04	0.87	0.22	2.1	0.43	4	2.1	15	75.6	165	1.95	6.2
30-60	6.31	0.78	0.15	1.9	0.44	3.7	1	13.5	13.2	136	2.10	9.0

The soils were slightly acid, deficient in organic matter and nitrogen, available phosphorus but adequately supplied with bases and trace elements.

Sorghum genotypes

The sorghum genotypes used in this research were selected from 108 genotypes obtained from sorghum growing semi-arid regions of Eastern, Coast and western parts of the country. All the genotypes were planted in short rains 2018 and reduced to 10 genotypes depending on grain yield and nitrogen uptake. These 10 genotypes plus a check were planted in short rains 2020. The experiment had three replicates.
The 11 sorghum genotypes for short rains 2020 were shortlisted based on higher grain yield, nitrogen uptake and ability to take up more than 60% of total nitrogen uptake from the soil (%Ndfs). Determination of %Ndfs and nitrogen uptake sources partitioning were done following the procedures described by Kathuli *et al.*, (2020).

Treatments and experimental design.

The treatments consisted of three nitrogen fertilizer rates (0, 6.5, and 32.5kg N ha-1). The rate of fertilizer NP used here are those recommended in the study area (Kathuli *et al.*, 2017) and 6.5kg N ha^{-1} was fixed at 20% of recommended fertilizer N to find if the genotypes can yield at very low levels of nitrogen. The experimental design was a randomized complete block design (RCBD) in split plots arrangement with three replicates. In short rains 2018, The experimental design was RCBD with split plot arrangement where fertilizer nitrogen was the main plot and 108 sorghum genotypes planted in split plots such that each line was a plot. Each nitrogen treatment was planted 12 sorghum genotypes spaced at 90 cm x 20 cm. The plots were 12m x 12m separated by 1m plot to plot and 2 m replicate to replicate. In short rains 2020, the shortlisted 11 sorghum genotypes (Table 2)

Table 2. Sorghum genotypes shortlisted for planting in semi-arid Machakos during SR 2020

Sorghum genotypes	Codes
Siaya Ngware (191)	SNGWAREA1
Rhoda Wayua Muthusi MKN (Kivila Kya Ivui)	MKNKKIRWMA2
Kitui Rasta (116) (Mary Mbisu)	KTIRASTAMMA3
Kitui Rasta (Malia Musomba)	KTIRASTAMMA4
Siaya Nyaktos (177)	SNYAKTOSA5
Kitaa kya Ivui (Andrew Mwalai)	TTKKIAMA6
Kilifi local V (197)	KLFLVA7
Embu local V (198)	EMBLVA8
Siaya Ochuti	SOCHUTIA9
Taita Taveta local (150)	TTLVA10
Gadam check (A11)	Gadam

were each planted in the main plot of 4m x 3m which accommodated four rows spaced at 90cm. In this season, nitrogen was applied in split plots. Two sorghum seeds were planted per hill spaced at 20cm and thinned to one plant per hill after germination. Nitrogen was applied at 0, 6.5 and 32.5kg N ha^{-1} in the subplots. 10kg P ha^{-1} was applied as basal fertilizer at planting in every plot due to phosphorus deficiency from initial soil analysis. The experiment in both seasons was weeded twice using a hoe with first weeding being done immediately after crop establishment and sprayed with insecticide to control cat worm. The second weeding was done at 5^{th} leaf stage.

Determination of nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) which measures plant nitrogen uptake in relation to soil nitrogen is expressed as NUE = PN/SN (Moll *et al.,* 1982; Dobermann, 2007; Shamme *et al.,* 2016). PN = plant nitrogen uptake, SN = soil nitrogen (from fertilizer and soil). NUE is a measure of how efficient the plant is in utilizing nitrogen from the soil (applied N + soil N) but since determination of mineralizable soil nitrogen was not analyzed, other methods kg grain kg $grain^{-1}$ (Moll *et al.,* 1982), kg dry matter kg shoot N^{-1} (Hawkesford *et al.,* 2014; Hirose, 2011) and TDM yield (Youngquist *et al.,* 1992) for determination of NUE were adapted.

Total dry matter yield of sorghum **(TDM)** is highly correlated (r^2=0.89) to PN/SN of sorghum which defines NUE such that, PS/SN = NUE for sorghum (Youngquist *et al.,* 1992). .Equation 1.

Nitrogen harvest index an indice of NUE, (**NHI) =** Grain N kg kg^{-1} N total in plant …Equation 2.

Agronomic efficiency an indice of NUE, (**AE)** = $(Y_{N\ rate}-Y_{No})/N_{rate}$ (Dobermann, 2007)...Equation 3.

Physiological efficiency an indice of NUE, (**PE) =** (kg yield increase per kg increase in N uptake from fertilizer) = $((Y_N- Y_o)/(U- U_o))$ (Dobermann, 2007)…………………….Equation 4.

Data analysis

After getting all the yield data, N-uptake analysis and computing NUE and its indices, means were calculated for every treatment. Effect of nitrogen fertilizer application on

Nitrogen recovery efficiency an indice of NUE, (**RE**) = (kg increase in N uptake per kg N applied) = $(U - Uo)/N_{rate}$ (Dobermann, 2007)…………………………………Equation 5.

Nitrogen internal utilization efficiency an indice of NUE, (**IE) =** (kg yield per kg nutrient uptake) = (Y/U) (Dobermann, 2007)………………………………….Equation 6.

Partial factor productivity an indice of NUE, (**PFP) =** (kg harvested product per kg nutrient applied) (Y/N_{rate})(Dobermann, 2007)……….Equation 7.

Nitrogen use efficiency **(NUE)** = kg grain/kg N grain (Moll *et al.,* 1982)…………...…Equation 8.

Nitrogen use efficiency **(NUE)** =TDM kg/kg N uptake (Hawkesford *et al.,* 2014; Hirose, 2011).....................................…..Equation 9.

Nitrogen uptake from the soil (Ndfs) was the difference between N-uptake when fertilizer N was applied and N uptake when no N fertilizer was applied. A crop takes up nutrient from the soil in equal amounts from all sources (Kathuli *et al.,* 2020)……………..………….Equation 10.

Harvesting and Analysis of plant materials

Two inner rows were harvested by cutting off the panicles into a labelled gunny bag and weighing immediately. All sorghum straws from the two inner rows were cut at the base and weighed immediately and weight recorded. A subsample was taken and chopped and resampled and weight taken immediately for determination of moisture content and dry stover weight. The panicles were dried to constant weight while straws were dried in open at $70^{O}C$ for 72 hours, and later sampled for nitrogen analysis using Kjeldahl method. The dried panicles were weighed, threshed and sorghum grains weighed. A sample of grains was taken for nitrogen analysis using Kjeldahl method for plant tissue analysis (Hinga *et al.,* 1980) at Kenyatta University Agricultural laboratories. Weight of dry stover was added to weight of dried panicles of the same treatment to get total dry matter yield (TDM) in $kgha^{-1}$. NHI, AE, PE, RE, IE, PFP, NUE were computed from the harvest data as given above for each treatment for every sorghum genotype.

sorghum genotype mean grain yield, stover weight, TDM yield, NHI, AE, PE, RE, IE, PFP and NUE within treatments, replicates, genotypes, and N-treatment x genotype interaction, N-treatment x replicates interaction and genotype x replicates interaction were analyzed using SAS software (SAS, 1990). Sources of variation in the experiment were the blocks, treatments, genotypes, and treatment interaction with genotypes. Means were separated using least significant different (LSD) and ranked by Duncan's multiple range test at 95% confidence limit. R^2 in SAS output was calculated as R^2=1- (Sum of squares error/sum of squares total). Bigger R^2 showed whether the data fitted well in the model. This was complemented by F statistic calculated using sum of squares from sources of variations and respective degrees of freedom at probability of less than 0.05.

Results

Effect of nitrogen application on sorghum yield parameters

The results on effect of nitrogen application on sorghum grain yield, stover weight, total dry matter yield, N uptake, nitrogen harvest index and NUE indices are shown in Table 3.

The results showed that nitrogen application at 6.5 kgha^{-1} and 32.5kgha^{-1} with basal 10kg P ha^{-1} significantly increased mean grain yield from 803 to 1436 (79%) and 803 to 2396kg ha^{-1} (198%) in SR 2018, 3155 to 3688kgha^{-1} (17%) and 3155 to 4256kgha^{-1} (35%) in SR 2020, mean stover weight from 1697 to 2887kgha^{-1} (70%) and 1697 to 4291kgha^{-1} (153%) in SR 2018 and 4929 to 5350kgha^{-1} (9%) and 4929 to 5832kgha^{-1} (18) in SR 2020. Mean total dry matter (TDM) yield was significantly increased from 2503 to 4323kgha^{-1} (73%) and 2503 to 4669kgha^{-1} (87%) in SR 2018 and 8086 to 9038kgha^{-1} (12%) and 8086 to 10088kgha^{-1} (25%) in SR 2020 respectively**.** This amounts to an average of 43% and 116% grain, 39% and 85% stover weight and 42% and 57% total dry matter increase due to application of 6.5 and 32.5 kg N ha^{-}1. Nitrogen response was linear and sorghum N uptake significantly increased with N application rate. Mean nitrogen use efficiency (NUE) (kg grain/kg grain or kg TDM/kg shoot N) of sorghum decreased with increasing N application. Mean nitrogen internal utilization efficiency (IE) (kg yield per kg nutrient uptake) was significantly higher at zero N application rate. Mean agronomic efficiency (AE) of nitrogen ($Y_{N\ rate}$ - Y_{No})/N_{rate} (kgkgN^{-1}), mean physiological efficiency (PE) (kg yield increase per kg increase in N uptake from fertilizer, mean nitrogen recovery efficiency (RE) (kg increase in N uptake per kg N applied) and mean partial factor productivity (PFP) of nitrogen (kg harvested product per kg nutrient applied) were all significantly higher at 6.5 kg N ha^{-1} + 10 kg P ha^{-1}. Mean nitrogen harvest index (NHI) was significantly increased by nitrogen fertilizer application but was not different for 0 and 6.5 kg N ha^{-1} application in SR 2018.

Sorghum yield parameters, nitrogen use efficiency and its indicators.

The results on sorghum genotype yield parameters and nitrogen use efficiency and its indices (IE, AE, PE, RE and PFP) are shown in Table 4. The data were obtained from statistical analysis on interaction of treatments and genotypes and ranking of the means for yield parameters and NUE and its indices to identify superior genotypes.

Table 3. Grain yield, stover weight, total dry matter (TDM), N uptake, NUE, and NUE indices of sorghum genotypes grown in Katumani during 2020 short rains season

Treatment	grain (kgha^{-1})		stover (kgha-1)		TDM (kgha-1)		N (kgha$^{-1)}$		NHI		NUE (moll)		NUE (Hi)		IE		AE		PE		RE		PFP	
	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
(0 kg Nha^{-1}	803^{c}	3155^{c}	1697^{c}	4929^{c}	2503^{c}	8086^{c}	25^{c}	36^{c}	.49^{b}	0.152^{b}	61^{a}	972^{a}	98^{a}	237^{a}	32^{a}	93^{a}								
(6.5 kg Nha^{-1}	1436^{b}	3688^{b}	2887^{b}	5350^{b}	4323^{b}	9038^{b}	49^{b}	52^{b}	.49^{b}	0.217^{a}	60^{b}	805^{b}	87^{b}	191^{b}	29^{c}	77^{b}	97^{a}	77^{a}	31^{a}	82^{a}	3.6^{a}	45^{a}	221^{a}	2.42^{a}
(32.5 kg Nha^{-1}	2396^{a}	4256^{a}	4291^{a}	5832^{a}	4669^{a}	10088^{a}	77^{a}	64^{a}	.52^{a}	0.22^{a}	58^{c}	672^{c}	86^{b}	171^{c}	31^{b}	72^{c}	48^{b}	72^{b}	30^{a}	34^{b}	1.6^{b}	47^{a}	74^{b}	0.83^{b}
Grand Mean	1545	3972	2959	5590	4502	9563	51	58	0.5	0.22	60	738	90	181	31	74	73	74	31	58	2.6	46	147	1.6
%CV	24	5.8	24	9.7	27	6.1	26	6.2	14	12.8	9	0	9	2.5	14	7.6	40	7.6	54	59	49	43	26	42
r^2	0.93	0.99	0.92	0.95	0.86	0.98	0.88	0.99	0.77	0.99	0.95	1	0.91	0.99	0.85	0.98	0.89	0.98	0.61	0.82	0.76	0.84	0.91	0.93
LSD($p \leq 0.05$)		117	111	277	148	300	1.7	1.8	0.1	0.014	0.79	0	1.3	2.3	0.7	2.9	4.6	2.9	2.6	17.5	0.2	10	5.9	0.35

Means in the same column followed by same letter are not significantly ($p \leq 0.05$) different by Duncan's multiple comparison test at 95% confidence limit.

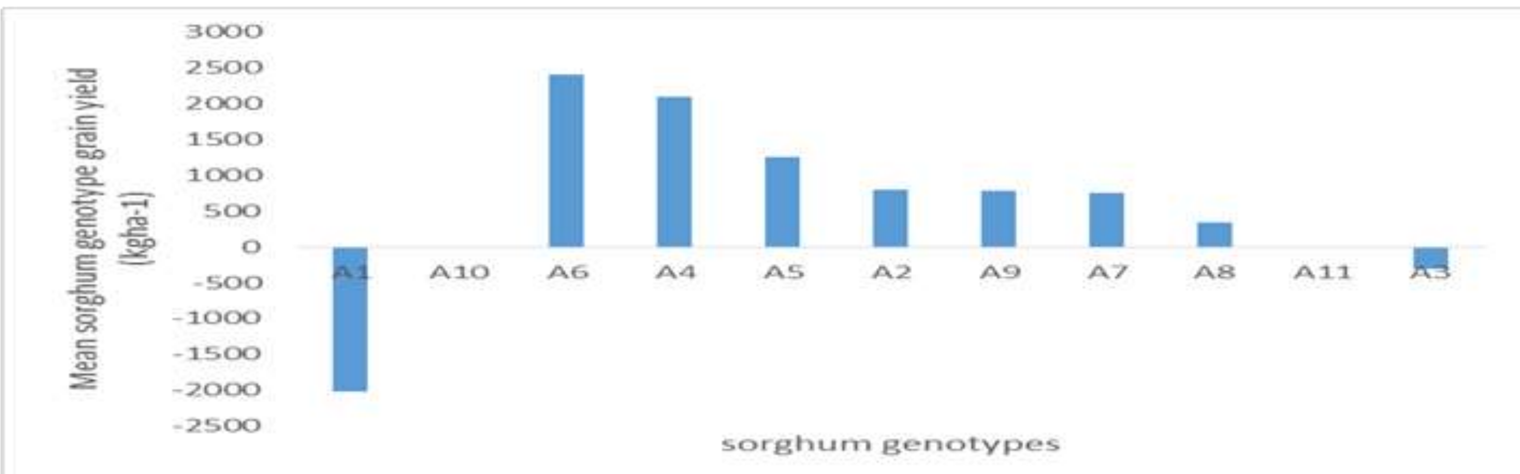

Figure 1. Mean sorghum genotype grain yield (kgha-1) in comparison to Gadam sorghum at semi-arid Machakos during short rains 2020.

A1 is SNGWAREA1, A2 is MKNKKIRWMA2, A3 is KTIRASTAMMA3, A4 is KTIRASTAMMA4, A5 is SNYAKTOSA5, A6 is TTKKIAMA6, A7 is KLFLVA7, A8 is EMBLVA8, A9 is SOCHUTIA9, A10 is TTLVA10, and A11 is Gadam.

Table 4. Sorghum genotype yield parameters and nitrogen use efficiency in semi-arid Machakos during short rains 2018 and 2020

code	Grain (kgha-1		stover (kgha-1		N uptake (kgha-1		TDM (kgha-1)		NHI		NUE (mol		NUE (H		IE		AE		PE		RE		PFP		Ndf
	201	2020	2018	2020	2018	2020	2018	2020	201	2020	2018	2020	201	202	201	202	201	202	201	202	201	202	201	202	201
A1	2342de	1390^{d}	3714^{nc}	3884^{d}	56^{jk}	36^{f}	6057kl	5274^{g}	0.49	0.05	83.0	863^{g}	92^{a}	149	41^{a}	41^{g}	145^{a}	41^{g}	42^{a}	33^{ab}	3.8^{e}	32^{c}	234^{ef}	1.24	43jk
A10	2311^{hi}	3408^{c}	4467^{gh}	3526^{d}	81cd	64^{bc}	6778hi	6934^{fg}	0.47	0.58	59.8	250^{h}	84^{ab}	110	28^{m}	53^{fg}	77^{hi}	53^{fg}	51^{a}	84^{a}	1.7^{g}	27^{d}	220^{fg}	3.24	68c
A6	3078^{ab}	5824^{a}	8555^{a}	7919^{a}	101a	58^{cd}	8630a	13743^{a}	0.39	0.11	66.9	1076	91^{a}	240	33^{m}	101	132^{a}	101	41^{a}	59^{ab}	4.8^{a}	42^{b}	268^{a}	1.57	87a
A4	3018^{a}	5514^{a}	5233^{ab}	6324^{bc}	92ab	40^{ef}	8183ab	11838^{b}	0.45	0.16	60.1	985^{f}	89^{ab}	300	34^{m}	139	103^{h}	139	30^{a}	70^{ab}	4.1^{a}	94^{a}	289^{a}	0.83	79a
A5	1861^{w}	4678^{a}	4577^{cd}	5330^{c}	72hi	52^{cde}	6438ij	10008^{c}	0.46	0.09	55.4	1041	91^{a}	198	25^{x}	92^{b}	119^{h}	92^{b}	28^{b}	68^{ab}	4.5^{a}	59^{b}	194^{m}	1.09	58ij
A2	2001no	4219^{b}	2702^{xy}	6291^{bc}	51jk	58^{cd}	4704^{yz}	10511^{b}	0.50	0.07	61.9	1148	97^{a}	182	41^{a}	73^{d}	90^{hi}	73^{d}	28^{b}	59^{ab}	3.1^{f}	69^{a}	191^{n}	0.93	38jk
A9	2329^{hi}	4201^{b}	4553^{cd}	4221^{d}	77gh	75^{b}	6883ef	8422^{ef}	0.50	0.60	59.9	95^{j}	91^{a}	113	30^{m}	57^{f}	137^{a}	57^{f}	28^{b}	64^{ab}	5.1^{a}	44^{b}	235^{b}	1.47	65fg
A7	2389de	4169^{b}	4577^{cd}	6921^{ab}	75gh	52^{cde}	6964ef	11090^{b}	0.46	0.08	58.7	992^{e}	97^{a}	216	33^{m}	81^{c}	87^{hi}	81^{c}	27^{b}	27^{b}	3.1^{f}	30^{c}	236^{b}	0.95	64fg
A8	1299^{w}	3762^{b}	4205^{jkl}	5874^{bc}	69jk	44^{ef}	6216ln	9636^{cde}	0.48	0.10	62.6	1011	89^{ab}	222	34^{m}	87^{c}	43^{i}	87^{c}	24^{b}	73^{ab}	3.1^{f}	49^{b}	192^{n}	1.37	56jk
A11	2255^{jk}	3416^{c}	3188^{xy}	5836^{bc}	63^{jk}	112^{a}	5414^{qr}	9251de	0.54	0.52	68.9	121^{i}	95^{a}	83^{h}	30^{g}	31^{h}	124^{g}	31^{h}	27^{b}	31^{ab}	4.9^{a}	10^{e}	267^{a}	3.91	73b
A3	1750^{w}	3113^{c}	2897^{xy}	5372^{c}	51^{jk}	47d^{ef}	4648^{yz}	8485^{ef}	0.51	0.06	67.1	1148	97^{a}	181	34^{m}	66^{e}	124^{f}	66^{e}	27^{b}	69^{ab}	3.2^{f}	50^{b}	249^{a}	1.28	38jk
Grand mean	1545	3972	2959	5590	51	58	4504	9563	0.5	0.22	59	816	90	181	31	74	73	74	31	58	2.6	46	147	1.6	38
%CV	24	5.8	24	9.7	21	6.2	21	6.1	15	12.8	8	0	9	2.5	14	7.6	40	7.6	54	59	49	43	26	42	28
r^2	0.93	0.99	0.92	0.95	0.94	0.99	0.94	0.98	0.77	0.99	0.95	1	0.91	0.99	0.86	0.98	0.9	0.98	0.61	0.82	0.76	0.84	0.9	0.93	0.91
LSD ($p \leq 0.05$	355	1171	671	1098	10	13	892	1825	ND	0.07	4.7	0	8	10	4	14	34	14	19	55	1.5	30	43	0.96	10

Means in the same column followed by same letter are not significantly ($p \leq 0.05$) different by Duncan's multiple comparison test at 95% confidence limit.

The results revealed that sorghum genotypes TTKKIAMA6, KTIRASTAMMA4, SNYAKTOSA5, MKNKKIRWMA2, SOCHUTIA9, EMBLVA8 and KLFLVA7

These sorghum genotypes had significantly higher mean NUE as measured by TDM yield $kgha^{-1}$ (Youngquist, *et al.,* 1992), mean NUE (kg grain kg grainN^{-1}) Moll *et al.,* (1982), and mean NUE (kg TDM kg N^{-1} shoot) Hirose (2011). Mean NUE indices measured by IE, AE, PE and RE were significantly higher in all tested sorghum genotypes incomparison to Gadam. Gadam had significantly very low mean nitrogen recovery efficiency and agronomic efficiency showing very low mean nitrogen use efficiency when compared to other genotypes in SR 2020. Sorghum genotypes TTKKIAMA6, KTIRASTAMMA4 and SNYAKTOSA5 had significantly low mean NHI.

Discussion

Effect of nitrogen fertilizer application on sorghum yield parameters and nitrogen use efficiency

These results agree with research hypothesis that, nitrogen fertilizer application at semi-arid Katumani-Machakos increases sorghum grain yield, stover weight and total dry matter yield. Nitrogen use efficiency determined by Moll *et al.,* (1982) and Hirose (2011) were all significantly higher at lower rates of nitrogen application. These results agrees with the findings of Kaizzi *et al.,* (2012) who found sorghum mean grain yield increase by 230% from application of 18- 34kg N ha^{-1} in semi-arid Uganda, Kathuli *et al.,* (2017) who found sorghum grain yield increase from 521-1106kg ha^{-1} (112%) in a season with very low(<200 mm) and erratic rainfall in semi-arid Ithookwe, Kitui due to application of 32.5kg N ha^{-1}, Workat *et al.,* (2020) who found sorghum grain yield to be increased by 122% by application of 30.75kg N ha^{-1} + 15kg P ha^{-1} in three equal split applications in the semi-arid Aybra-Sekota-Ethiopia and sorghum grain increase by 174% when 20.5kg N ha^{-1} + 10kg P ha^{-1} in three equal split applications was applied in semi-arid Shumshiba-lasta Lalibela Ethiopia. Masebo and Menamo (2016) showed sorghum grain yield of 3896 kg ha^{-1} with application of 92kg N ha^{-1} + 30 kg P ha^{-1} in semi-arid Derashe Woreda, Ethiopia. significantly out yielded Gadam sorghum. The grain yield increments above the Gadam sorghum grain yield (local check) are illustrated in Figure 1.

However, the results disagree with findings of Bosire (2019) who found no significant response to N and P application on Gadam and Seredo sorghum cultivars grown at KALRO Machakos during long and short rain seasons in 2014 and 2015.

This was attributed to response of applied nitrogen fertilizer as the soil analysis showed the soils at the study site were low in nitrogen and organic matter. Soil total nitrogen determined by Kjeldahl method (Bremner, 1960) was deficient (0.15%) in 0-30cm soil depth indicating response was more likely. Other factors that influence N response are available phosphorus, soil texture and amount of rainfall (Bosire, 2019; Schnier *et al.,* 1996) and in this case available phosphorus was low and was corrected by application of basal 10kg P ha^{-1}. The N response was linear indicating that for sorghum, higher rates of nitrogen can be applied though this can be influenced by amount of rainfall in the season (Schnier *et al.,* 1996) as fertilizer use in semi-arid lands is very risky (FURP, 1994). The results on effect of nitrogen application on sorghum grain yield can be recommended for sorghum cultivation in other semi-arid regions with similar soil nitrogen status and rainfall (Schnier *et al.,* 1996) as these are key determinants on whether response to N application on sorghum is likely or not. Since a linear response to nitrogen application was found, it is suggested that application of higher rates of N can be tried in future.

NUE (moll) determined by method of Moll *et al.,* (1982) and NUE (Hi) determined by procedure of Hirose, (2011) were all significantly highest at lowest N application rate. This implied that the crop utilized nitrogen well when it was applied in small amounts and there were little N losses. This follows the determination of NUE = PN/SN. Soil nitrogen is a sum of N–uptake from fertilizer (Ndff) and soil Ndfs). N-uptake from soil = N-uptake when fertilizer N is applied –N uptake when N is not applied. These results agree with research hypothesis that nitrogen fertilizer application has an effect on sorghum yield parameters. The results were in agreement with other findings (Mahama, 2012) that nitrogen use efficiency of sorghum genotypes is largest at 0kg N application, findings of Shamme *et al.,* (2016) that NUE of sorghum was highest at low N application rates in Kellem-Wollege zone of Ethiopia. Results further agree with findings of Bollam *et al.,* (2021) who found high NUE sorghum genotypes from a study of 60 genotypes experimented using 0, and 50% N rates recommended in ICRISAT site Patancheru, India. More findings of Sigua *et al.,* (2018) that, NUE for sorghum was increased (60.5 and 57.1%) by application of 85 and 170kg N ha^{-1} with 100% supplementary irrigation at the Coastal Plains Research Center near Florence, SC. USA. Results from this study further agrees with Shamme *et al.,* (2016) findings that, NUE and other sorghum cultivar yield parameters were increased by nitrogen application with a decrease in NUE at higher rates of nitrogen fertilizer application at Haro Sabu Agricultural Research Center (HSARC) in western Ethiopia, Oromia regional state. NUE of maize was also found to be highest at low N application of 2.47g/plant vs 9.89g/plant (Moll *et al.,* 1982). NUE of sorghum is highest at low N and hence the need to know which sorghum genotypes have a high yield and high NUE for efficient sorghum production in semi-arid lands. This implied that the soils were responding to nitrogen application. These results can be applied beyond Katumani provided rainfall amounts and distribution, daily temperatures and soil test nitrogen is the same.

Agronomic efficiency of nitrogen (AE) was significantly increased by application of 6.5kg N ha^{-1} to 77kg kg^{-1}N and 97kg kg^{-1}N. These findings imply that 6.5kg N ha^{-1} with basal 10kg P ha^{-1} can be recommended for sorghum growing because it gives 77- 97kg of sorghum grain for every kg of nitrogen fertilizer applied. These results can be used beyond Katumani provided the rainfall is the same and soils are N deficient and good agricultural practices for sorghum are followed. The limitations on these findings is that if the rains fail or are less than 200mm in a season with poor distribution, then AE of nitrogen may not be achieved due to risk of using fertilizers in dry land soils (Schnier *et al.,* 1996). These results agree with the research hypothesis that, nitrogen application has an effect on agronomic nitrogen use efficiency and the findings of Dobermann (2007) that AE of nitrogen can be greater than 25kg grain kg^{-1}N in well managed fields with adequate rainfall well distributed in the season.

Nitrogen internal utilization efficiency (IE) (kg yield per kg nutrient uptake) is the ability of a plant to transform nutrients acquired from all sources (soil, fertilizer) into economic yield (grain). IE was significantly higher (93kg kgN^{-1} uptake) at 0kg N ha^{-1} + 10kg P ha^{-1} followed by 6.5kg Nha^{-1} (77kg kgN^{-1}uptake). This result agrees with findings that, most crops have IE within 30-90kg kg^{-1} (Dobermann, 2007; Muchow, 1998) and higher in low N soils with good management. The soils at the experimental site were low in nitrogen.

Physiological efficiency (PE) = Physiological efficiency of applied N (kg yield increase per kg increase in N uptake from fertilizer) is another index of NUE. It was significantly increased (32 to 82kg kgN^{-1} increase in uptake) by Nitrogen application at 6.5kg N ha^{-1}. This result agrees with research hypothesis that, nitrogen application has an effect on nitrogen use efficiency of sorghum and further agrees with findings of Dobermann (2007) that PE for nitrogen is 40-60kg kg^{-1} and > 50kg kg^{-1} in well-managed fields at low levels of N use or low soil N supply. It implies that use of 6.5kg N ha^{-1} + basal 10kg P ha^{-1} in semi-arid lands is recommended for increased sorghum grain yield and nitrogen use efficiency. Limitations are when rainfall is not adequate and good agronomic practices for sorghum are not followed.

Nitrogen recovery efficiency (RE) which measures Apparent crop recovery efficiency of applied nutrient (kg increase in N uptake per kg N applied) was not significantly affected by Nitrogen fertilizer treatments because it depends on the congruence between plant demand and nutrient release from fertilizer (Dobermann, 2007) and the N fertilizer treatments were applied in the same day.

Partial factor productivity (PFP) (grain yield kg kgN^{-1} applied) which measures productivity of the nutrient (kg harvested product per kg nutrient applied) was significantly increased by

Nitrogen application at 6.5kg N ha^{-1} but was below levels of PFP 40-80kg kg^{-1} reported by Dobermann (2007) in SR 2020. The levels obtained in this experiment are low because grain yields were low for the fertilizer rates applied. Computation of PFP used rate of applied nitrogen but did not incorporate mineralizable N from soil organic matter. Further research is required on sorghum partial factor productivity to include soil N supply.

Sorghum genotype yield parameters and nitrogen use efficiency

The local check Gadam sorghum had significantly high N-uptake than all genotypes studied in SR 2020. Genotypes TTKKIAMA6, KTIRASTAMMA4 and SNYAKTOSA5 had significantly low N uptake and high grain yield implying they are N-efficient sorghum genotypes. These genotypes had significantly low nitrogen harvest index (NHI) implying they are not miners of soil nitrogen but they use little nitrogen to give significantly high grain yields. This implies that, despite the sorghum genotypes having significantly higher grain yield, their grains contained very low nitrogen and can be improved further for specific needs like brewing when compared to Gadam.

These results agree with research hypothesis that, Sorghum genotypes nitrogen harvest index, nitrogen use efficiency and productivity are significantly affected by soil nitrogen. This implies that, Sorghum genotypes have different nitrogen harvest index (NHI) which can be low or high depending on genotype remobilization of N in grain (Shamme *et al.,* 2016; Mahama *et al.,* 2014; Mahama, 2012). In other cereal crops, NHI is positively correlated to grain yield (Fageria, 2014) and this depends on the duration the crop remobilizes nitrogen into grain formation. This trait is genetic and can be used for selecting genotypes for high yield and protein content (Moll *et al.,* 1982; Fageria, 2014). The high yielding sorghum genotypes with low NHI are suitable for low soil fertility status because they are not miners of nitrogen but has high grain yield. These are suitable for low soil fertility in semi-arid lands. These results can be generalized beyond Katumani provided soils are N deficient with same rainfall regimes. However, the results need to be validated in farmers' fields.

All tested genotypes had significantly high NUE (55 to 1148kg grain kg^{-1}grainN, RE (1.7 to 94kg increased N uptake kg^{-1}N applied), AE (41 to 145kg grain kg^{-1} N fert. applied), PE (24 to 84kg grain increase kg^{-1} increase in N fertilizer uptake) and nitrogen internal utilization efficiency (IE) (28 to 139kg grain kg^{-1} N uptake.) than the check (Gadam) showing they are efficient in nitrogen use than Gadam. These results confirm that Sorghum genotypes have different NUE and its indices as reported by Shamme *et al.,* (2016), Mahama, (2012) and Moll *et al.,* (1982). However, the results can differ within seasons due to difference in rainfall amounts. These results show that the tested 10 sorghum genotypes are efficient in N use than the recommended Gadam sorghum grown in semi-arid lands and there is need to incorporate these sorghum genotypes in sorghum breeding program to develop efficient N sorghum varieties for the semi-arid lands of the country and beyond.

Conclusion

Nitrogen application at 6.5kg ha^{-1} and 32.5kgha^{-1} with basal 10kg P ha^{-1} significantly increased sorghum grain yield, stover weight and total dry matter (TDM) yield by 43% and 116%, 39% and 85%, and 42% and 57% respectively. Nitrogen use efficiency (NUE) of sorghum decreased with increasing N application. Nitrogen internal utilization efficiency (IE) was significantly higher at zero N application rate. Agronomic efficiency (AE) of nitrogen, Physiological efficiency (PE), Nitrogen recovery efficiency (RE) and partial factor productivity (PFP) of nitrogen were all significantly higher at 6.5kg N ha^{-1} + 10kg P ha^{-1}.

All tested sorghum genotypes had significantly high NUE (55 to 1148kg grain kg^{-1}grain N, RE (1.7 to 94kg increased N uptake kg^{-1}N applied), AE (41 to 145kg grain kg^{-1} N fert. Applied), PE (24 to 84kg grain increase kg^{-1} increase in N fertilizer uptake) and nitrogen internal utilization efficiency (IE) (28 to 139kg grain kg^{-1} N uptake.) than the check (Gadam). Sorghum genotypes TTKKIAMA6, KTIRASTAMMA4 and SNYAKTOSA5, had significantly high grain yield and low NHI than the check (Gadam sorghum) and are considered suitable for low soil fertility situations in semi-arid lands and needs to be incorporated in sorghum breeding to develop N efficient sorghum for the country and beyond.

These results can be applied beyond Katumani provided rainfall and soil nitrogen is the same. It is proposed that ^{15}N isotope dilution technique should be used to show why NUE of many cereals is largest at low N application rates. It is further suggested to estimate mineralizable N from the soil so that NUE = PN/NS be analyzed and compared with the current NUE determinations.

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