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Effect of Nitrogen Fertilizer on Water Use Efficiency of 11 Selected Sorghum Genotypes Grown in Semi-Arid Regions in Kenya.

1*Kathuli Peter., J.M. Kinama[2], S.N Nguluu[3], O.M. Kitonyo[2], Catherine Muui[4], R.M. Muasya[3].

[1]*KALRO-Machakos, Kenya. Box 340 – 90100 Machakos.*
[2]*Department of plant science and crop protection, University of Nairobi.*
[3]*Department of agricultural science and dry land agriculture, southeastern university.*
[4]*Department of crop science, Kenyatta University.*
***Corresponding author:** peterkathuli@yahoo.com*

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Abstract

Sorghum production in semi-arid lands is constrained by soil fertility and inadequate moisture which is acerbated by climate change. A study was carried out in SR 2018 and 2020 at Katumani, Machakos to evaluate effect of nitrogen fertilizer on water use efficiency and determine water efficient sorghum from 11 selected genotypes using gadam as a check. First season was used to shortlist genotypes based on high grain yield, large nitrogen use efficiency and nitrogen uptake from the soil. The experimental design was a RCBD with split-plot arrangement. Sorghum genotypes plus check were planted in the main plot and nitrogen fertilizer at three levels (0, 6.5, 32.5 kg ha^{-1}) with 10 kg P ha^{-1} as basal fertilizer was applied in the split plots. Potential evapotranspiration (ETo) was used to determine WUE. The experiment was replicated three times. The results showed that, use of nitrogen fertilizer at (6.5 kg N) ha^{-1} and (32.5 kg N) ha^{-1} significantly increased WUE by 12-25% and 17-35% on biomass and grain productivity mm^{-1} of rainwater. The sorghum grain yields were significantly correlated (r^2=0.8) to mean WUE. Five genotypes had significantly large WUE. It was concluded that use of fertilizer nitrogen significantly increased WUE of sorghum genotypes in semi-arid Machakos and there are five genotypes with significantly large WUE than Gadam and are recommended for farmer cultivation and incorporation in breeding Programme for development of drought resistant sorghum.

Key words: Nitrogen fertilizer, sorghum genotypes, WUE, semi-arid lands, potential evapotranspiration.

Introduction

Sorghum production in semi-arid lands is constrained by drought, poor soil fertility and genotype traits (Mwamahonje et al., 2021; Omoyo, 2015; Bosire et al., 2018; Kathuli et al., 2017; Amelework et al., 2016; Muui et al., 2013). Sorghum grain yield increase as rainfall increases in a season and decreases as rainfall decrease through decreased growth development and less seed formation. Higher variability (45%) in sorghum yields can be attributed to climate change which affects the soil resources for sorghum production in semi-arid environments (Bosire, 2019). Soil moisture limits production of grain sorghum in semi-arid lands (Masaka et al., 2021; Assefa et al., 2010). This is enhanced by poor soil fertility in semi-arid environments (Zaongo et al., 1997). In semi-arid West Africa, nitrogen application increased sorghum grain yield by 20% and water use efficiency by 21% (Zaongo et al., 1997). Soils in semi-arid lands in Kenya (Itabari et al., 2013), East Africa (Egeru et al., 2019) and beyond (Queiroz et al., 2018) are low in nitrogen which limits sorghum and other crops production. The semi-arid soils in the country are low in organic matter (≤ 0.2% OM), nitrogen (≤ 0.2%N) and phosphorus (≤ 20 mg/kg soil) (NAAIAP, 2014) and will require application of these deficient nutrients for increased water use efficiency and sorghum productivity.

Sorghum responds very well to application of nitrogen fertilizer on most soils (Kaizzi et al., 2012) although it is considered a low fertilizer input crop. It responds to nitrogen and phosphorus application and other good agricultural practices in dry lands of eastern Kenya (Kathuli et al., 2017) and beyond (Zaongo et al., 1997). Nitrogen application for sorghum cultivation depends on soil nitrogen status, weather, rainfall amounts, intended yield and nutritional status and can vary from 0 to 150 kg N ha^{-1} (Workat et al., 2020; Wang et al., 2014). In semi-arid Guinea Savanna, sorghum response to nitrogen application is generally about 40-50 kg Nha^{-1} (Buah and Mwinkaara, 2009) with 40 kg N ha^{-1} being the most economic N rate. This rate of nitrogen application resulted in 281% marginal rate of return in a study on sorghum response to nitrogen fertilizer in the above area. However, variable sorghum responses to application of N fertilizer has been observed in sorghum due to climate, soil fertility and genotypic factors across seasons and locations (Mahama, 2012; Mahama et al., 2014). This is associated with differences in soils to supply N and in sorghum efficiency of recovery of applied N and differences in nitrogen uptake and utilization efficiencies (Wang et al., 2014). In other semi-arid lands, nitrogen fertilizer use for sorghum has been found to be within 18 – 34 kg N ha^{-1} resulting in mean sorghum grain yield increase of 230% (Kaizzi et al., 2012). Use of 32.5 kg N ha^{-1} in semi-arid Kitui resulted in sorghum grain yield increase of (112%) 521-1106 kg ha^{-1} in a season with very low rainfall (Kathuli et al., 2017). Similarly in semi-arid Ethiopia (Workat et al., 2020) 30.75 kg N ha^{-1} + 34.5 kg P_2O_5 ha^{-1} is recommended for sorghum production at Aybra-Sekota and 20.5 kg Nha^{-1} plus 23 kg P_2O_5 ha^{-1} at Shumshiha-Lasta Lalibela. The rate of fertilizer nitrogen and phosphorus applied on soil for crop production depends on soil analysis and rainfall regime (Schnier et al., 1996).

Several sorghum genotypes are grown in sorghum growing areas in semi-arid areas in the country (Muui et al. 2019) attaining less than 0.5t ha^{-1} due to climate change which fluctuates soil moisture conditions and soil quality. Sorghum genotypes have been found to have different yields and tolerance to climate change in Sudan (Abdalla and Gamar, 2011). This suggests that among the sorghum genotypes grown in semi-arid regions in the country there are some which could be drought tolerance as measured by their productivity (grain ha^{-1}mm^{-1} rainfall) and water use efficiency in scarce soil moisture conditions brought by inadequate rainfall conditions as a result of climate change which manifests itself in terms of frequent dry spells in the seasons, erratic and inadequate rainfall leading to inadequate soil moisture and low crop production. Sorghum growth and yield is affected by low soil fertility and climate change particularly rainfall amounts in the season (Omoyo, 2015; Bosire, 2019; Kathuli et al., 2017) in semi-arid lands. Sorghum yields increase as rainfall increases in a season and decreases as rainfall decrease through decreased growth development and less seed formation. Bosire (2019) while working in semi-arid Machakos demonstrated that Gadam sorghum yield was insignificantly increased by changing climate and nitrogen application through modelling. Zaongo et al., (1997) demonstrated that sorghum grain yield increased as water use efficiency when soil moisture in the soil was increased under conservation tillage with and without nitrogen application within semi-arid Niger in West Africa.

Farmers are growing many sorghum genotypes with minimum soil fertility improvement or none attaining very low yields (< .5t ha-1) (Muui et al., 2019; 2013). The reasons for low yield are due to low use of inputs, inappropriate genotypes and inadequate soil moisture among others (Omoro, 2013). It would be justified to evaluate sorghum genotype response to nitrogen application and effect of nitrogen application to grain yield and water use efficiency. Sorghum with higher water use efficiency and biomass yield will be drought tolerant and suitable for semi-arid conditions (Youngquist et al., 1992).

Water use efficiency (WUE) which is a measure of the ability of a crop to use available water from the soil is a measure of a crop to survive in water scarce environment and is referred to as crop resistance to drought (Blum, 2005). It can be estimated from crop productivity per milliliter of rain water. WUE = crop yield/T_{crop} = kg/mm rainfall. The available water (T_{crop} (mm)) for crop growth is the amount of rainfall water used by a crop to grow. From crop water balance equation, crop water use (cwu) or Tcrop (mm) = P-R-D-E-T_{weeds} – Δs (Ajeigbe et al., 2018; Abunyewa et al., 2011; Kinama et al., 2005; Itabari, 1999) where Tcrop = transpiration, P = precipitation, R = runoff, D = drainage, E = soil evaporation and Δs is change in soil water stored within the rooting zone.

Measurement of water use efficiency of sorghum genotypes grown in semi-arid areas in the country will give an indication of genotypes that survive in drought prone areas and are suitable for growing in semi-arid lands because they will have higher water use efficiency and grain yield (WUE = kg yield ha^{-1} mm^{-1} rainwater = crop yield/T_{crop} (mm rainfall used by crop for growth and yield) (Kinama et al., 2005). Tcrop is water transpired by crop as it grows and develops grains and biomass and WUE can also be expressed as WUE = kg biomass ha^{-1} mm^{-1} rainwater. Different sorghum genotypes have different genes that are responsible for differences in physiological functions like carbon dioxide exchange rate, transpiration efficiency, stomata conductance, leaf water potential, nodal root angle formation and root distribution and osmotic adjustment and regulation of leaf canopy temperatures all geared to better soil water use efficiency in adaptation to drought conditions (Gaosegelwe, 1988). From assessment of effect of nitrogen fertilizer application on water use efficiency of sorghum genotypes found in the sorghum growing semi-arid lands, it may be possible to find those genotypes which are efficient users of soil moisture and nitrogen and are adaptable for low soil fertility semi-arid lands.

Drought tolerance is defined as the capacity of a plant to develop and produce in water deficit environment. It is measured as (kg biomass yield/evapotranspiration) and referred as water use efficiency of the crop (WUE). Evapotranspiration is a measure of water transpired by a crop as it develops. It can be determined from meteorological weather data on pan evaporation and use of pan coefficient and sorghum crop coefficient where evapotranspiration can be estimated. Drought tolerance can be expressed as water use efficiency (WUE) where WUE = (crop yield kg/ET_C) ($kgha^{-1}m^{-3}$). ETc = Epan* Kp *kc. Epan is pan evaporation, Kp is pan coefficient and Kc is crop coefficient. ETc is potential evapotranspiration of the crop. ETo =Epan * kp.

Potential evapotranspiration (ETo) is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of an extended disease free short green crop/grass (alfalfa), completely shading the ground, of uniform height (8-15cm), well fertilized, actively growing and with adequate water status in the soil profile. It is a reflection of the amount of energy in form of heat available to evaporate water, and available wind to transport the water vapour from the ground up into the atmosphere (Kassam and Smith; 2001). ETo is also estimated by the use of the Penman- Monteith method. The FAO-56 Penman-Monteith method refers to the use of an equation for computing water evaporation from vegetated surfaces by use of lysimeters. From pan evaporation, ETo is calculated after taking into account of pan coefficient.

ETo = Epan * Kp when there is no crop cover. When there is a crop cover, ETo = Epan * Kp * kc = ETc potential evapotranspiration of the crop. WUE = crop yield/ETc. Another method for determination of WUE = crop yield kg/T_{crop} where crop transpiration is measured directly (Yunxuan et al., 2018) or measured from water balance equation after measurement of soil evaporation using micro lysimeters, runoff via runoff plots, and deep seepage and rain gauges for water on top and below canopy (Kinama et al., 2005). Crop water = Precipitation-runoff- soil evaporation – deep seepage-water intercepted by crop canopy (Kinama et al., 2005). Water use efficiency can be measured from crop water balance WUE = crop yield kg/crop water use, using crop water balance (Ajeigbe et al., 2018; Abunyewa et al., 2011). Pan evaporation method is significantly ($p < 0.001$) well correlated to other methods for estimation of potential evapotranspiration (ET_{O}) (Amatya et al.

2018). Water use efficiency (WUE) is also calculated as units of dry grain yield per unit cropland (Y, kg ha^{-1}) divided by the units of water consumed by the crop (ETc, mm) to produce that yield (Ibragimov et al., 2007). WUE = Y/ET. Where WUE refers to crop water use efficiency and the unit is kg m^{-3} which can be unified with the unit kg ha^{-1} mm^{-1} following: WUE $_a$ (kg m^{-3}) = WUE $_b$ (kg ha^{-1}mm^{-1}) /10 (Ibragimov et al., 2007). ET is potential evapotranspiration, and usually expressed as a depth of water (mm). ETc is crop evapotranspiration. Water use efficiency can be measured in terms of crop transpiration efficiency = biomass/water transpired or determination of biomass accumulated because it is correlated to carbon assimilation and leaf area development (Shaobing and krieg, 1992). Transpiration efficiency (TE), an important component of WUE, is defined as TE = biomass/water transpired. At the leaf level, TE is defined as the intrinsic WUE; that is, the ratio of instantaneous CO_2 assimilation (A) to transpiration (T) = A/T (Vadez et al., 2014) and this can also be used to determine WUE of a crop after measuring transpiration using lysimeters. WUE can also be estimated from productivity per unit of water used to produce the productivity (Feisota et al., 2017), WUE= P/V. P = Productivity, V = volume of water. Units: kg.m^{-3}.

Past Studies have shown that crop production and water use efficiency can be increased in semi-arid lands by insitu rainwater harvesting when used together with soil fertility improvement (Kathuli et al., 2015; Kathuli et al., 2010; Steiner and Rockstrom, 2003). In arid and semi-arid regions of eastern Africa, insitu rainwater harvesting increases rain water productivity or efficiency from 1-1.5 to 3-4.5 kg mm^{-1} rain (Steiner and Rockstrom, 2003). The objectives of this paper were: 1) To determine the effect of nitrogen fertilizer on sorghum genotypes water use efficiency in semi-arid Machakos.2) To determine relationship between sorghum genotype yield and water use efficiency. 3) Find out sorghum genotypes with higher water use efficiency in semi-arid lands.

Materials and Methods.

Study site

The study was conducted in short rains season of 2020 at KALRO Katumani, Machakos (1° 35'S and 37° 14' E, 1600 m above sea level). The area has mean annual temperatures varying from a minimum and maximum of 13.7°C and 24.7°c respectively (Wamari et al., 2012) with a bimodal rainfall pattern with long and short rainfall seasons occurring from March to May (MAM) and from October to December (OND) respectively. The average rainfall for the short and long seasons is 250 and 350 mm respectively with annual mean of 655 mm (Wamari et al., 2012). Long rains are very unreliable, poorly distributed and insufficient for crop production (Itabari et al., 2011). The soils have sandy clay loamy texture, have surface crusting and low in organic matter and prone 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), very low in nitrogen (0.15%) and organic matter (0.88% org. carbon), low phosphorus (17.2 mg/kg), slightly acidic (pH 6.10) with adequate potassium (2.05 Cmol/kg) and trace elements in top soil 0-30 cm depth as determined using recommended methods in our country (Hinga et al., 1980).

Sorghum genotypes

The 10 sorghum genotypes used in this study were shortlisted from 108 genotypes obtained from sorghum growing regions in semi-arid lands in the country. The sorghum genotypes were shortlisted based on high nitrogen use efficiency measured as kg grain kg grain N^{-1} (Moll et al., 1982), kg total dry matter (TDM) kg plant N^{-1}(Hirose, 2011), percent N derived from the soil (%Ndfs) and TDM yield (Youngquist et al., 1992). A list of sorghum genotypes planted in short rains 2018 from where the 10 genotypes were shortlisted based on above criteria are shown in Table 1.

Table 1: sorghum genotypes' grain yield, stover weight and nitrogen use efficiency in semi arid Machakos during short rains 2018

Genotype codes	Grain yield (kgha-1)	Stover wt. (kgha-1)	N uptake (kgha-1)	NUE (kg grain kg grainN-1)	Ndfs (kgha-1)	%Ndfs	%Ndff
A99. RastaKTI (BendetilaKitiliMiriam)	3580a	5934	104	60	78	75	25
A96. Ochutisia(SamsonOtienoOdel)	3426ab	5814	110	59	69	63	37
A29. Kitaa kya ivui MKN(philipMakauKingoku)	3321abc	6103	113	57	73	65	35
A69. LocalTT(MaryStellaKavuli)	3233abcd	6336	108	63	89	82	18
A21. Kari Mtama1mks(josephatMbetekanyele)	3036abcde	4648	90.7	58	49	54	46
A32. Kitaa kya ivui TT(Andrew mwalai)	3009abcdef	5820	92	74	61	66	34
A35. Kivila kya ivui mkn(Rhoda wayua Muthusi)	2974abcdef	5035	89	75	42	47	53
A36. Kivila kya ivui TT(Agnes Wilson)	2923abcdefg	5878	93	65	80	86	14
A93. Nyakabalasia(Samson Otieno Odero)	2908abcdefg	4837	89	56	69	78	22
A66. LocalTT(Judith Leshempta)	2873abcdefgh	4989	107	45	55	51	49
A94. Nyaktossia (PhilomenaNgara)	2867abcdefghi	5196	91	56	56	62	38
A41. Localbrownmks(Josephat Mbete Kanyele)	2848abcdefghij	4895	80	80	43	54	46
A80. Ngwaresia(Gideon Ndege)	2843abcdefghij	5612	82	84	63	77	23
A71. LocalTT(Schola Mwethya)	2790abcdefghijk	5497	94	51	68	72	28
A68. LocalTT(MariamDzame)	2765bcdefghijkl	4207	85	60	60	75	25
A101.Rasta Kti(Malia Musomba)	2763bcdefghijkl	5178	80	72	43	60	40
A81. Ngwaresia(Mary Onyango)	2733bcdefghijklm	4166	73	70	44	60	40
A14. Gadamsia(Caleb Ochieng)	2674bcdefghijklmn	4584	79	65	53	67	33
A45. LocalKLF(Jonathan Tole)	2670bcdefghijklmn	4981	80	64	52	81	19
A38. Lightbrownembu(Teresia Nthua)	2621cdefghijklmno	4603	90	64	63	70	30
A15. Gadamsia(JamesNgesaAjuma)	2567cdefghijklmnop	3764	67	68	44	66	34
A58. Localredkti(JosephNthigaSanai)	2533cdefghijklmnop	4961	87	55	61	70	30
A108.Vaasyakti(BendetilaKitiliMiriam)	2500defghijklmnop	4494	86	45	69	80	20
Grand mean	2005	3770	65	59	40	-	-
lsd($p<0.05$)	85.6	146	2.4	1.4	23	-	-
r2	0.89	0.89	0.91	0.9	0.99	-	-
CV	27	25	24	15	1.3	-	-

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.

Gadam sorghum variety was used as the check.

Experimental design and plot layout

Experimental design was RCBD with split plot arrangement where sorghum genotypes were in main plot and fertilizer nitrogen in the split plots. Below is experimental lay out in a North to South orientation.

North

South

		Rep. 1							**Rep.2**							**Rep. 3**				
	Acc.	**NO**		**N1**		**N2**	**1**	**Acc.**	**N1**		**N2**		**NO**	**1**	**Acc.**	**N2**		**NO**		**N1**
1	Siaya Ngware(191)							Kilifi local							Siaya Nyaktos					
														2						
2	Rhoda wayua (Kivila kya ivui)						**2**	Malia Musomba(ktirasta)							Rhoda wayua (Kivila kya ivui)					
3	Kitui rasta(116)mary mbisu						**3**	Embu local V						**3**	Gadam check					
4	Malia Musomba(ktirasta)						**4**	Kitaa kya ivui(Andrew malai)						**4**	Kilifi local V					
5	Siaya Nyaktos(177)							Gadam check							Embu local V					
							5							**5**						
6	Kitaa kya ivui(Andrew malai)							Rhoda wayua (Kivila kya ivui)							Siaya Ngware					
7	Kilifi local V(197)						**6**	Taita Taveta local						**6**	Kitui rasta(mary mbisu)					
8	Embu local V(198)							Siaya Nyaktos							Ochuti Siaya					
							7							**7**						
9	Siaya Ochuti							Siaya Ngware							Kitaa kya ivui(Andrew malai)					

							8													
10	Taita Taveta local(150)							Ochuti Siaya						**8**	KTI Rasta (malia Musomba)					
							9													
11	Gadam check						**10** **11**	Kitui rasta(mary mbisu)						**9** **10** **11**	Taita Taveta local					

Nitrogen fertilizer treatments and sorghum planting.

N0. (0 kg N) ha^{-1}
N1. (6.5 kg N) ha^{-1}.
N2. (32.5 kg N) ha^{-1}

The plots were 4 m x 3 m separated by 0.5m and accommodated four lines of sorghum with inter row spacing 90 cm and 20 cm hill to hill. Two sorghum seeds were planted and immediately thinned to one plant after germination to minimized nutrient loses. Acc = sorghum genotype, N0= 0 kg N ha^{-1}, N1= 6.5 kg N ha^{-1}, N2=32.5 kg N ha^{-1}. The nitrogen treatments were randomized within the experimental layout as shown. Sorghum genotype names were as given in this layout. Phosphorus was applied as basal fertilizer during planting at 10 kg P ha^{-1} as triple super phosphate while nitrogen was applied at 0, 6.5 and 32.5 kg N ha^{-1} as calcium ammonium nitrate as top dressing fertilizer 20 days after germination and after first weeding. Insecticide marshal was used to control shoot fly immediately after germination. Sorghum was thinned to one plant per hill within first week of crop establishment.

Sorghum harvesting

Two inner rows from four rows planted in each plot were harvested. Panicles from the two inner sorghum rows were cut off into a gunny bag and weight taken using an electronic hanging balance to three decimals. All the stover from the two inner row was cut at the base and weighed immediately. A sample of the stover was chopped and weighed as stover subsample for moisture analysis. This was done for all plots in each replicate. The panicles harvested were dried to constant weight for two weeks, threshed and winnowed and weighed. The stover subsample were oven dried at 70°C for three days and weighed as dry stover weight for moisture calculation. All grain and stover data were calculated in $kgha^{-1}$ dry weight.

Determination of sorghum genotype water use efficiency.

Pan evaporation (Epan) or evaporation data for short rains season 2020 was obtained from meteorological weather station at KALRO Katumani (Table 2).

Table 2: Pan evaporation data during short rains 2018 and 2020 at KALRO Katumani, Machakos

	SR 2018			**SR 2020**		
	OCT	NOV	DEC	OCT	NOV	DEC
Mean evaporation (mm)/day (Pan coefficient = 0.5)	5.4	4.5	4.4	5.8	4.2	5.2
Evaporation (mm)	167.4	135	136.4	179.8	126	161.2
Rainfall mm	23.5	138.4	214.8	20.4	116.2	29.5
Solar radiation(Langles /day)	244.6	296.2	294.2	263.8	234.9	279.9

The Epan has been multiplied by Kp pan coefficient to give potential evapotranspiration ETo. ETo * Kc =ETc. Kc = crop coefficient. Sorghum crop coefficient used here was 1.18 (Shenkut et al., 2013) taken at mid-growing season.

Sum evaporation for the SR 2020 season = Sum (179.8+126+161.2) = 467 mm= Epan. **Equation** (1).
ETo= Epan * kp =467 *0.5= 233.5 mm. **Equation 2**.
ETc=potential evapotranspiration for sorghum at Katumani = ((233.5 mm)*1.18 = 275.53 mm/season. **Equation** (3)
WUE = grain yield $kgha^{-1}$/ETc ($kgha^{-1}mm^{-1}$) ETc= Evapotranspiration or crop water use mm (Cwu) for every sorghum genotype in every nitrogen treatment for all replicates. **Equation** (3). Evapotranspiration (Crop water use) the consumptive use of each treatment at various stages of the sorghum crop was

estimated using the Water Balance Equation (FAO, 56): $ET = P \pm \Delta S + R + D$. P = Precipitation (Rainfall) in mm, ΔS = Change in moisture storage (mm), R = Runoff (mm). Crop water use (Cwu) = precipitation-evaporation - runoff - drainage - change in soil moisture. Runoff=0, drainage =0, change in soil moisture=0. Cwu =precipitation-evaporation (Ajeigbe et al., 2018; Abunyewa et al., 2011)
Productivity = Grain yield kg ha^{-1} was obtained from the experiment in the field. Kg grain or biomass /ha .**Equation** (4).
Example 1: If grain yield = 1639 kg ha-1, ET_c = 275.53 mm SR 2020 (calculated from meteorological data for Katumani (Table 2)), WUE =1639/ (275.53). Kg ha^{-1} mm^{-1}. = **5.95** kg ha^{-1} mm^{-1}.
WUE = productivity/volume of water used for productivity (Feisota et al., 2017). **Equation** (5). This can also be used to compute WUE but the values will differ. From relationship (1mm rainfall = 10 m^3ha^{-1}), (Ibragimov et al., 2007) and
Rainfall SR 2020 = (Total rainfall in season = 166.1 mm = 166.1 *10 m^3 ha-1 =1661 m^3 eqn. (**6**)
WUE_a (kg m^{-3}) = WUE_b (kg $ha^{-1}mm^{-1}$) /10 (Ibragimov et al., 2007) for conversion of units **Equation** (7).
Example 2: WUE = 1639kg ha^{-1}/1661 m3.ha^{-1} = **0.987** kg ha^{-1}.m^{-3}. For this case, runoff = 0, Drainage = 0, evaporation from surface = 0 **(**Feitosa et al., 2017). Example 1 was used to compute water use efficiency of sorghum genotypes in this research work.

Data analysis

All data for sorghum grain yield, stover weight and water use efficiency were analyzed for variations within treatment means of nitrogen fertilizer, sorghum genotype yields and experimental errors arising from treatments and genotypes using single factor analysis of variance. Then using F statistic arising from ratio of mean sum of squares N treatments/mean sum of squares experimental error and ratio of mean sum of squares genotype treatments/mean sum of squares experimental of genotypes and comparing with F statistic at $\alpha = 0.05$ it was possible to see if nitrogen treatments affected WUE, grain yield and stover weight of the sorghum genotypes and whether sorghum genotypes had significantly different WUE. Effect of treatments on WUE and effect of genotypes on WUE were separated using Duncan's multiple comparison test at 95% confidence limit using Fishers' least significant difference.

Simple regression of sorghum biomass yield with water use efficiency was carried out to see if they are significantly correlated and if higher sorghum yield in semi-arid lands implies higher water use efficiency and drought resistance.

Results

The results on effect of nitrogen fertilizer application on water use efficiency, and yield of sorghum genotypes is shown in Table 3.

Table 3: Effect of nitrogen application on WUE and yield of sorghum genotypes at Katumani, Machakos during short rains 2020.

Treatments	**Water use efficiency**			**Grain yield**	**Stover weight**	**Total dry matter yield**
	Biomass kgha^{-1}mm^{-1}	grain kgha^{-1}mm^{-1}	grain kgha^{-1}m^{-3}	kgha^{-1}	kgha^{-1}	kgha^{-1}
(0 kg N)ha^{-1}	29.35^{c}	11.46^{c}	1.146	3155c	4929c	8086c
(6.5 kg N)ha^{-1}	32.8^{b}	13.39^{b}	1.339	3688b	5350b	9038b
(32.5 kg N)ha^{-1}	36.61^{a}	15.45^{a}	1.545	4256a	5832a	10088a
GM	32.92	13.43	1.343	3972	5590	9563
CV	7.1	7.2	0.72	5.8	9.7	6.1
r^2	0.97	0.98	0.98	0.99	0.95	0.98
LSD($p \leq 0.05$)	1.15	0.48	0.048	117	277	300

Means followed by same letter in same column are not significantly different by to Duncan's multiple comparison test at 95% confidence limit. The results showed that WUE of sorghum grain or biomass and yield parameters were linearly increased by nitrogen fertilizer application at the study site. WUE was linearly increased by nitrogen application at 6.5 kg N ha^{-1} and 32.5 kg N ha^{-1} indicating that sorghum genotypes responded to nitrogen application resulting in increased biomass and grain production. A plant grows as it transpires and biomass production by the plant increases as plant transpired water which measures water use by the plant.

Results on analysis of simple regression of sorghum mean total dry matter yield visa-vice water use efficiency at Katumani Machakos is shown in Fig. 2.

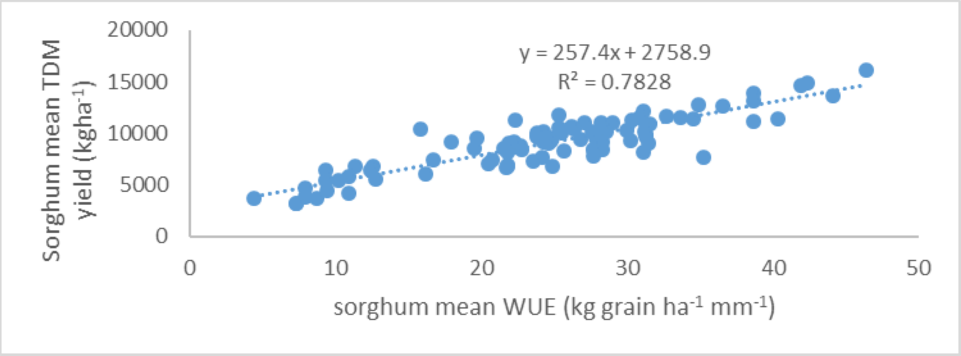

Fig. 2: simple regression analysis of mean sorghum grain yield (kgha^{-1}) vs mean water use efficiency at Katumani, Machakos during SR 2020.

The results shows that, total dry matter (TDM) yield of sorghum genotypes obtained in semi-arid machakos were linearly correlated to how much rain water the crop was able to use from the soil for production. Implying that sorghum mean total dry matter yields are correlated (r^2=0.8) to amount of rain water sorghum can extract from the soil to accumulate the dry matter. Obtained sorghum total dry matter yield in semi-arid land can be a measure of drought resistance of the sorghum genotype.

Results on water use efficiency of selected sorghum genotypes from semi-arid regions in the country grown in Katumani, Machakos are shown in Table 4.

Table 4: Water use efficiency of selected sorghum genotypes from semi-arid grown at Katumani, Machakos during short rains 2020.

Genotypes	**Water use efficiency (WUE)**		
	Biomass kgha^{-1}mm^{-1}	**Grain kg ha^{-1}mm^{-1}**	**Grain kgha^{-1}m^{-3}**
Kitaa kya Ivui A6(Andrew Malai)	47.61^{a}	19.90^{a}	1.990^{a}
Kitui Rasta A4(Malia Musomba)	40.30^{b}	18.71^{ab}	1.871^{ab}
Kilifi local V A7(197)	38.74^{bc}	14.68^{bcd}	1.468^{bcd}
Rhoda Wayua A2 (Kivila Kya Ivui)	36.19^{bc}	14.38^{cd}	1.438^{cd}
Gadam check A11	34.94^{bcd}	11.79^{cde}	1.179^{cde}
Siaya Nyaktos A5 (177)	33.99^{bcd}	15.75^{abc}	1.575^{abc}
Embu local V A8 (198)	32.44^{de}	12.54^{cde}	1.254^{cde}
Siaya Ochuti A9	28.75^{de}	14.25^{cde}	1.425^{cde}
Kitui Rasta A3 (116)(Mary Mbisu)	28.56^{de}	10.17^{e}	1.017^{e}
Taita Taveta local A10 (150)	23.80^{f}	11.06^{de}	1.106^{de}
Siaya Ngware A1 (191)	16.8^{F}	4.52^{f}	0.452^{f}
GM	32.92	13.43	1.343
CV	7.1	7.2	0.72
r^2	0.97	0.98	0.98
l.s.d ($p \leq 0.05$)	6.7	4.2	0.42

Means followed by same letter in same column are not significantly different by to Duncan's multiple comparison test at 95% confidence limit.

The results shows that four sorghum genotypes had significantly ($p \leq 0.05$) higher water use efficiency implying their genetic trait to utilize rain water more effectively for growth and productivity is semi-arid areas. *Kitaa kya Ivui* (A6 Andrew Malai), *Kitui Rasta* (A4 *Malia Musomba*), *Kilifi* local (A7 197) and Rhoda *Wayua* (A2 Kivila kya Ivui) were found to be significantly superior in rain water utilization (biomass kg $ha^{-1}mm^{-1}$) in semi-arid Machakos in comparison to Gadam sorghum which is recommended for growing in semi-arid lands in the country. When water use efficiency was expressed as grain kg ha^{-1} mm^{-1}, five sorghum genotypes (*Kitaa kya Ivui* (A6 Andrew Malai), *Kitui Rasta* (A4 *Malia Musomba*), *Kilifi* local (A7 197), Rhoda *Wayua* (A2 Kivila kya Ivui and Siaya Nyaktos A5 (177)) were found to have significantly higher WUE than recommended sorghum variety for semi-arid lands (Table 4).

Discussions

Effect of nitrogen fertilizer application on sorghum genotype water use efficiency

Nitrogen fertilizer application at 6.5 kg N ha^{-1} and 32.5 kg N ha^{-1} significantly increased water use efficiency of sorghum genotypes in semi-arid KALRO Machakos by 12-25% on biomass production per mm of rainwater in short rains 2020 and 17-35% on grain production per mm of rainwater in the same season (Table 3). These results do not agree with the research hypothesis that, Water use efficiency of sorghum genotypes is not significantly affected by soil nitrogen. The results agree with the findings of Ajeigbe et al., (2018) in semi-arid Sudan savanna zone in Nigeria were they found WUE of sorghum genotypes increased by 48-55% at BUK and 54-76% at Manjibir due nitrogen fertilizer application at 60 kg N ha^{-1}. This implies that, WUE of sorghum genotypes is enhanced by soil moisture and available nitrogen in soil or applied as fertilizer and it is more when nitrogen is applied in low N soils. These results shows that, sorghum responds very well to nitrogen fertilizer applicant (Sigua et al., 2018; Gebremariam and Assefa, 2015; Kaizzi et al., 2012) and response is enhanced by availability of moisture in the soil (Kathuli et al., 2017). These results can be generalized beyond Katumani in other semi-arid lands. This is supported by the fact that the area has to be a hot semi-arid land receiving not more than 350 mm of rainfall distributed over 3 months when sorghum is in the field and soil has to be low ($N < 0.2\%$) in soil nitrogen. The water use efficiency reported here could have been large because the site had low soil nitrogen implying possible nitrogen fertilizer response and the rains were below long term mean average (350 mm). The small increment in WUE of sorghum at Katumani Machakos is because of low rainfall (166.1 mm) received in the season. More research is needed to show what will happen to WUE if rains are more in the season although it can be speculated that productivity will increase (Kathuli et al., 2017; Zaongo et al., 1997) increasing WUE as reported in Sahelian ecosystem in Niger were nitrogen application increased sorghum WUE by 21% (Zaongo et al., 1997).

Simple regression analysis of sorghum total dry matter yield visa-vice water use efficiency at Katumani in semi-arid Machakos.

Measurement of water use efficiency of crops involves measurement of crop water (Yunxuan et al., 2018; Kinama et al., 2005), estimation of crop water use after measurement of soil evaporation using lysimeters (Kinama et al., 2005) or measurement of potential evapotranspiration (Amatya et al. 2018) of the crop and is very involving. High yielding sorghum genotypes are found to be having large water use efficiency which is correlated to sorghum crop grain yield. In this study simple correlations of mean sorghum genotype total dry matter yields against mean water use efficiency was carried out. Mean sorghum total dry matter yield was significantly correlated ($r^2 = 0.8$) to mean sorghum genotype water use efficiency implying that in semi-arid lands, sorghum with large grain yields have large water use efficiency and are more drought resistant than sorghum genotypes with low yields. This criteria can be used for selecting sorghum genotypes with large water use efficiency and resistance to drought for food security and sorghum improvement in semi-arid lands. These results concurs with findings of Feitosa et al., (2017) that, in semi-arid Brazil, sorghum with the highest mean grain yield (2143 kg ha^{-1}) had the highest mean water use efficiency (8.8 kg ha^{-1} mm^{-1}). The results concurs with the findings of Hatfield and Dold (2019) that crop biomass or grain yield is correlated to water use efficiency and maximum sorghum grain (13.12 t ha^{-1}) and biomass (24.91 t ha^{-1}) obtained from twice irrigated sorghum had highest WUE of 4.53 kg ha^{-1} mm^{-1} than once irrigated sorghum (Mahinda et al., 2018). The relationship of mean sorghum total dry matter yield and WUE in semi-arid lands implies that higher yielding genotypes are drought resilience from their WUE and are adaptable to drought conditions.

Water use efficiency of selected sorghum genotypes from semi-arid regions in the country grown in Katumani, Machakos.

Water use efficiency of 10 selected sorghum genotypes were compared to Gadam sorghum, a variety recommended for growing in semi-arid regions in the country. The results are shown in Table 4. The results revealed that five sorghum genotypes (*Kitaa kya Ivui* (A6 Andrew Malai), *Kitui Rasta* (A4 *Malia Musomba*), *Kilifi* local (A7 197), Rhoda *Wayua* (A2 Kivila kya Ivui and Siaya Nyaktos A5 (177) had significantly ($p < 0.05$) greater water use efficiency in comparison to the check (Gadam sorghum variety) (Table 4). A crop with high water use efficiency is presumed an efficient water user and hence drought resistant (Yunxuan et al., 2018; Amatya et al., 2018). These genotypes had 4-36% more water use efficiency than recommended gadam sorghum variety at Katumani in semi-arid Machakos showing potential for increased sorghum grain and biomass productivity under prevailing semi-arid conditions. The results are within what is reported for grain sorghum that WUE is within 1 to 29 kg ha^{-1} mm^{-1} (0.1 to 2.9 kg ha^{-1}m^{-3}) (Mahinda et al., 2018; Feitosa et al., 2017; Abunyewa et al., 2011). These results on water use efficiency are more than those reported in semi-arid northern brazil by Feitosa et al., (2017) where sorghum had WUE of between 0.21 kg ha^{-1}m^{-3} to 0.88 kg ha^{-1}m^{-3} (2.1 kg ha^{-1} mm^{-1} to 8.8 kg ha^{-1} mm^{-1}) and greater than those reported for sorghum in semi-arid Sudan savanna zone in Nigeria (Ajeigbe et al., 2018). At this area, sorghum WUE was 1.7-11.5 kgha^{-1}mm^{-1} at *Manjibir* and 4.4-12.9 kgha^{-1}mm^{-1} at *BUK* sites respectively. The differences could be attributed to soil fertility levels and calculation because Feitosa et al., (2017) did not subtract evaporation water from rain water. Their WUE = productivity/crop water rainfall without subtracting any water loss from the field through soil evaporation. These results disagrees with the hypothesis that water use efficiency of sorghum genotypes is not significantly affected by soil nitrogen. These findings confirms that some sorghum genotypes are more resistant to drought stress as impacted by inadequate soil moisture leading to low grain productivity. Similar observations were observed in Sudan where performance of 19 sorghum genotypes were assessed under water stress conditions at Shambat Experimental farm and found to respond differently to water stress with two genotypes giving higher yields than the rest (Hamza et al., 2016). Similarly Abdalla and Gamar (2011) while researching on performance of selected sorghum genotypes under rain-fed areas of Sudan showed that some sorghum genotypes mature early and have high yields and are resistant to drought and are adaptable to wide range of environments. These results concurs with the findings of Jabereldar et al., (2017) that, a sorghum genotype was found to be tolerant to induced drought through irrigation at university of Kordofan, Sudan. This genotype had both higher seed yield and water use efficiency than other four genotypes when drought was induced at 8th leaf stage. The implications of the results is that there are some sorghum genotypes with significantly high water use efficiency in semi-arid lands and are adaptable to drought conditions and can be introduced to sorghum breeding program to develop nitrogen and water efficient sorghum for semi-arid lands. These results can be generalized beyond Katumani in other semi-arid lands because Katumani is one of dry land representative site in semi-arid lands of eastern Kenya.

Conclusions

Use of fertilizer nitrogen significantly increased (12-25% WUE on biomass and 17-35% grain production kg ha^{-1} mm^{-1} of rainwater) WUE of sorghum genotypes in semi-arid Machakos. There are five sorghum genotypes (Kitaa kya Ivui A6 (Andrew Malai), Kitui Rasta A4 (Malia Musomba), Kilifi local V A7 (197), Kivila Kya Ivui MKN A2 (Rhoda Wayua Muthusi) and Siaya Nyaktos A5 (177) with significantly large grain yield and WUE than Gadam and are recommended for farmer cultivation and incorporation in breeding Programme for development of water efficient drought resistant sorghum. Sorghum genotype total dry matter yield in semi-arid lands is significantly correlated to WUE of sorghum (grain kg ha^{-1} mm^{-1}) and can be used as indicator of drought resistant sorghum selection in the region.

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