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# Effect of nitrogen fertilizer on water use efficiency of selected sorghum genotypes grown in semi-arid regions in Kenya

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## Abstract

Sorghum yield in semi-arid regions is constrained by soil fertility and moisture stress which are worsened by climate variability. Water and nitrogen present a strong interplay in sorghum growth and yield in dry lands. In view of these constraints, selection of genotypes that concurrently maximize the use of these two resources is important. A study was carried out in short rains 2018 and 2020 at Katumani, Machakos to evaluate effect of nitrogen fertilizer on water use efficiency and determine water efficient sorghum genotypes. The experimental design was a randomized complete bock design with split-plot arrangement. Sorghum genotypes plus a 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 water use efficiency. 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 sorghum water use efficiency (WUE) from 9.68 to 16.69 (72%) and 9.68 to 25.8 (170%) biomass kgha$^{-1}$mm$^{-1}$ and 3.14 to 5.55 (77%) and 3.14 to 9.28 (196%) grain kgha$^{-1}$mm$^{-1}$ , respectively, in SR 2018 and from 29.35 to 32.8 (12%) and 29.35 to 36.61 (25%) biomass kg ha$^{-1}$ mm$^{-1}$ and from 11.46 to 13.39 (17%) and 11.46 to 15.45 (35%) grain kg ha$^{-1}$ mm$^{-1}$ , respectively, in SR 2020. The sorghum mean total dry matter and grain yields were significantly correlated ($R^2$ = 0.8-0.9) to mean WUE. Five genotypes had significantly large WUE. It was concluded that nitrogen fertilizer significantly increased WUE of sorghum genotypes in semi-arid Machakos and there are five genotypes with significantly higher WUE than Gadam and are recommended to farmers and incorporation in breeding programmes for drought tolerant sorghum.

**Keywords:** *Nitrogen fertilizer, sorghum genotypes, WUE, semi-arid regions, potential evapotranspiration*

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## Introduction

Sorghum is grown in semi-arid lands due to its ability to survive severe and recurrent droughts when other crops fail (Keith *et al.,* 2019; Assefa *et al.,* 2017). It is an efficient C4 crop with high water use efficiency and efficient in conversion of carbon into starch and globally feeds over 500 million people in more than 30 countries in semi-arid lands (Hariprasanna and Rakshit, 2016). Sorghum production in semi-arid lands is constrained by inadequate soil moisture, severe and recurrent droughts (Mwamahonje *et al.*, 2021; Masaka *et al.,* 2021; Assefa *et al.,* 2017; Assefa *et al.,* 2010), low soil fertility (Mishra *et al.,* 2015; Muui *et al.,* 2013) and planting of inappropriate genotype traits (Amelework *et al.,* 2016; Omoro, 2013). Its grain yield increase as rainfall increases in a season and decreases as rainfall decrease through decreased growth development and less seed formation (Bosire *et al.,* 2019; Msongaleli *et al.,* 2017). 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; Omoyo, 2015). Soil moisture limits production of grain sorghum in semi-arid lands (Masaka *et al.,* 2021; Assefa *et al.,* 2017; Amelework *et al.,* 2016). The decline in sorghum productivity in semi-arid lands is enhanced by low soil fertility (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 the country (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 lands soils in the country are low in organic matter ($\leq$ 0.2% OM), nitrogen (< 0.2%N) and phosphorus ($\leq$ 20 mg/kg soil) (NAAIAP, 2014) and will require application of these deficient nutrients for increased growth, water use efficiency and sorghum productivity.

In semi-arid lands, sorghum response to N fertilizer application is variable depending on soil N, rainfall amounts (Yu and Zhao, 2022; Workat *et al.,* 2020; Kathuli *et al.,* 2017; Kaizzi *et al.,* 2012; Baa and Mwinkaara, 2009), climate, genotypic factors (Mahama *et al.,* 2014; Mahama, 2012;) and sorghum N use efficiency (Wang *et al.,* 2014).

Sorghum grain yield has been found to be increased as WUE when soil moisture in the soil was increased under conservation tillage with and without nitrogen application within semi-arid Niger in West Africa (Zaongo *et al.,* 1997). 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 millilitre of rain water, that is, 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 $T_{crop}$ (mm) = P-R-D-E-$T_{weeds}$ – $\Delta$s (Ajeigbe et al., 2018; Abunyewa *et al.,* 2011; Kinama *et al.,* 2005; Itabari, 1999) where $T_{crop}$ = transpiration, P = precipitation, R = runoff, D = drainage, E = soil evaporation and $\Delta$s is change in soil water stored within the rooting zone.

Tcrop is water transpired by crop as it grows and develops grains and biomass. It is potential evapotranspiration of the crop and can be measured directly as crop transpiration using a special tool that allows for measurement of crop transpiration (WUE = crop yield kg/$T_{crop}$ , where crop transpiration ($T_{crop}$) is measured directly (Yunxuan *et al.,* 2018). WUE can be measured from crop water balance (Ajeigbe *et al.,* 2018; Abunyewa *et al.,* 2011). It can further be measured from potential evapotranspiration (ETc) of the crop and can be expressed as WUE = kg biomass $ha^{-1}$ $mm^{-1}$ rainwater. ETc is calculated from potential evaporation (ETo) obtained from evaporation pan data considering its pan coefficient (kp) and crop transpiration coefficient (kc) (Allen *et al.,* 1998). ETo is also estimated by the use of the Penman- Monteith method (Allen *et al.,* 1998). Pan Evaporation method is significantly (p< 0.001) well correlated to other methods for estimation of potential evaporation ($ET_{O)}$ (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/ETc. Where WUE refers to crop water use efficiency and the unit is kg $m^{-3}$ which can be unified with the unit kg $ha^{-1}$ $mm^{-1}$. ETo is potential evaporation, and usually expressed as a depth of water (mm). Water use efficiency can also be measured in terms of crop transpiration efficiency (TE) = biomass/water transpired or determination of biomass accumulated because it is correlated to carbon assimilation and leaf area development (Shaobing and Krieg, 1992). 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 $m^{-3}$.

In sorghum growing semi-arid lands in the country, farmers grow many sorghum genotypes with or without minimum soil fertility improvement attaining very low yields (< .5t $ha^{-1}$) (Muui *et al.,* 2019; 2013). The reasons for low yield are hypothized to be due to low use of inputs, inappropriate genotypes, and lack of knowledge on sorghum genotypes with better nitrogen use efficiency and higher water use efficiency and inadequate soil moisture conditions among others. Elsewhere, 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 tolerant as measured by their productivity and water use efficiency (grain $ha^{-1}mm^{-1}$ rainfall) in scarce soil moisture conditions.

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 from 1-1.5 to 3-4.5 kg $mm^{-1}$ rainwater (Steiner and Rockstrom, 2003). It would be justified to evaluate sorghum genotypes response to nitrogen application and effect of nitrogen application on 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).

The objective of this study was to determine the effect of nitrogen fertilizer on sorghum genotypes yield, water use efficiency, identify genotypes with higher water use efficiency in semi-arid lands and evaluate the relationship between genotype yield and water use efficiency. The working hypothesis was that, use of nitrogen fertilizer increases sorghum genotypes yields and water use efficiency differently and sorghum genotypes yield increased as water use efficiency of the genotypes and there are some sorghum genotypes with high water use efficiency and can be recommended for sorghum breeding program for semi-arid lands.

## Materials and Methods

### *Study site*

The study site was located at KALRO Katumani in Machakos County (Figure 1).

**Figure 1**

*The experimental site at KALRO Katumani, Machakos*

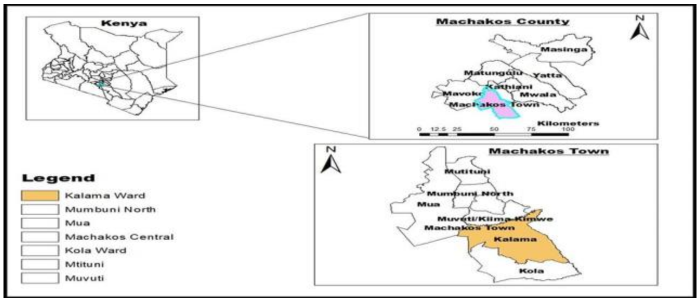


**Table 1**

*Katumani Machakos meteorological station short rains 2018/2020 OCT-DEC seasons*

| Date | **2018** | | | | | | | | | | | | **2020** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JULY | AUG | SEP | OCT | NOV | DEC |
| 1 | 0 | 6.6 | 5.9 | 1 | 12.9 | 15.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 1.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 |
| 3 | 0 | 0 | 23.3 | 2.2 | 2.6 | 0 | 11.8 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 |
| 4 | 0 | 0 | 37.5 | 0.5 | 0 | 6.5 | 0 | 0 | 0 | 0 | 0 | 6.8 | 0 | 0.3 | 0 |
| 5 | 0 | 0 | 6.4 | 16.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2.9 | 0 |
| 6 | 0 | 0 | 0 | 40.5 | 0 | 0 | 3.7 | 1.6 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 |
| 7 | 12 | 0 | 39 | 9.1 | 0 | 0 | 4.5 | 0 | 0 | 0 | 0 | 1.4 | 0 | 0 | 0 |
| 8 | 0.2 | 0 | 4.7 | 8.1 | 0 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.3 | 0 |
| 9 | 0 | 0 | 1.4 | 0 | 0 | 0 | 0 | 0 | 5.3 | 1.5 | 0 | 0 | 0 | 9.5 | 2.3 |
| 10 | 0 | 0 | 21.2 | 0 | 0 | 0 | 0 | 2.6 | 0.2 | 0 | 0 | 0 | 0 | 14.8 | 0 |
| 11 | 0 | 3.2 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0 | 0 | 1.5 | 0 |
| 12 | 0 | 0 | 26.9 | 25.9 | 0 | 1.4 | 0 | 0 | 7.2 | 0 | 0 | 0 | 0 | 0.8 | 1 |
| 13 | 0 | 0 | 22 | 2.3 | 14.3 | 0 | 4.3 | 0 | 3.8 | 0 | 0 | 0 | 0 | 14.1 | 0 |
| 14 | 0 | 0 | 11.9 | 10 | 1.2 | 0 | 2.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 |
| 15 | 0 | 0 | 4.2 | 7 | 3.6 | 0 | 1.4 | 0.3 | 0 | 0 | 0 | 0 | 0 | 3.5 | 0 |
| 16 | 0 | 0 | 0 | 0 | 2 | 0 | 17.9 | 3.2 | 0 | 0.3 | 0 | 0 | 0 | 0.4 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | 4.1 | 32.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 0 | 66.2 | 9.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8.7 | 6.4 | 0 |
| 20 | 0 | 5 | 0 | 0 | 0 | 6.5 | 65.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 9 | 0 | 0 | 0 | 0 | 12.8 | 0 | 0 | 0 | 0 | 0 | 0 | 3.6 | 0 |
| 22 | 1.8 | 0 | 0 | 0 | 1.8 | 0 | 31.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 3 | 0.2 | 0 | 0 | 0.3 | 0 | 2.4 | 0 | 0 | 0 | 0 | 0 | 0 | 1.7 | 0 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 1.9 | 6.2 | 0 | 1.7 | 0 | 0 | 45.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 |
| 25 | 0 | 30 | 0.1 | 32.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | 2.9 | 3.3 | 0.5 | 1.9 | 11.8 | 61 | 20.8 | 0 | 0 | 0 | 0 | 0 | 9.4 | 0.2 | 0 |
| 27 | 1.9 | 0 | 0 | 25.7 | 7.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 36.3 | 0 |
| 28 | 0 | 8.7 | 0 | 3.9 | 0 | 28.4 | 10 | 0 | 0 | 0 | 0 | 0 | 2.3 | 9.5 | 0 |
| 29 | 0 | 0 | 0 | 0 | 0 | 42.4 | 5.8 | 0 | 0 | 0 | 0 | 0 | 0 | 5.1 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0 | 13.7 |
| 31 | 0 | | 0 | 44.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | | 12.5 |
| **TOTAL** | **23.5** | **138.4** | **214.8** | **233.4** | **57.9** | **179** | **273.9** | **7.7** | **16.3** | **1.8** | **1.8** | **9.2** | **20.4** | **116.2** | **29.5** |
| TOTAL SEASON | | | **376.7** | | | | | | | | | | | | **166.1** |

The study was conducted in the short rains season of 2020 at KALRO Katumani, Machakos ($1^{o}$ 35'S and $37^{o}$ 14' E, 1600 m above sea level). The area has mean annual temperatures varying from a minimum and maximum of $13.7^{O}$C and $24.7^{O}$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 rain 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). Rainfall amounts and distribution at the study site for short rain seasons in 2018 and 2020 is shown in Table 1.

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 chromic luvisols (FAO/UNESCO, 1990), very low in nitrogen (0.15%) and organic matter (0.88% organic 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 areas of the country. The sorghum genotypes were shortlisted based on high nitrogen use efficiency measured as 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).

***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. Sorghum genotypes *Siaya Ngware*, *Kivila kya Ivui* (MKN), *Rasta Kitui* (116) Mary Mbisu, *Rasta Kitui* (Mali Musomba), *Nyaktos* (177) Siaya, *Kitaa kya Ivui* (Andrew Malai), *Kilifi local* (107), *Embu local* (109), *Ochuti* (Siaya), *Taita Taveta local* and Gadam local check were planted in a main plot of 4m x 9m. This plot had been split into 3 plots of 4m x 3m which were nitrogen fertilizer plots. Each sorghum genotype was planted four lines in a plot of 4m x 3m separated from other plot by 0.5 m path. One replicate had 33 plots and the experiment was replicated three times. The experiment was laid out in a north to south orientation with a west aspect.

***Nitrogen fertilizer treatments and sorghum planting***

There were three nitrogen fertilizer treatments; -N0 (0 kg N) $ha^{-1}$, N1 (6.5 kg N) $ha^{-1}$, and N2 (32.5 kg N) $ha^{-1}$). The plots were 4 m x 3 m separated by 0.5 m 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. The nitrogen treatments were randomized within the experimental 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 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$^{o}$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) data for short rains season 2018 and 2020 was obtained from meteorological weather station at KALRO Katumani (Table 2).

**Table 2**

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

In SR 2020, sum evaporation for the SR 2020 season = Sum (179.8+126+161.2) = 467 mm= Epan. While in SR 2018, sum evaporation= sum (167.4 +135 +136.4) = 438.8 mm…. ……………………………………………………… …………**Equation** (1).

ETo= Epan * kp =467 *0.5= 233.5 mm. for SR 2020 and 438.8*0.5=219.4 mm for SR 2018……………. **Equation** (2).

ETc=potential evapotranspiration for sorghum at Katumani during SR 2020 = ((233.5 mm)*1.18 = 275.53 mm/season. While ETc for SR 2018 = 219.4 *1.18= 258.89 mm/season. WUE = grain yield kgha$^{-1}$/ETc (kgha$^{-1}$mm$^{-1}$……………………… **Equation** (3).

Crop evapotranspiration (ETc) was determined from water balance equation (Allen *et al.*, 1998). ETc = Evapotranspiration or crop water use mm (Cwu) for every sorghum genotype in every nitrogen treatment for all replicates.

Evapotranspiration (Crop water use) the consumptive use of each treatment at various stages of the sorghum crop was estimated using the Water Balance Equation (Allen *et al.,* 1998): ET = P ± ΔS + 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$^{-1}$ ………. **Equation** (4).

**Example1**: This is based on equation 3 above such that, 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$^{-1}$.

Another method for working WUE. WUE = productivity/volume of water used for production (Feisota *et al.,* 2017) …... **Equation** (5).

This procedure can also be used to compute WUE but the values will differ. (1mm rainfall = 10 m$^3$ha$^{-1}$).

If Rainfall SR 2020 = (Total rainfall in season) = 166.1 mm, then volume of water for production = 166.1 *10 m$^3$ ha$^{-1}$ =1661 m$^3$ha$^{-1}$………………… **Equation.** (6)

Then, WUE $_a$ (kg m$^{-3}$) = WUE $_b$ (kg ha$^{-1}$mm$^{-1}$) /10 (Ibragimov *et al.,* 2007) from conversion of units……………. **Equation** (7).

**Example 2**: WUE = 1639kg ha$^{-1}$/1661 m$^3$ha$^{-1}$ = **0.987** kg ha$^{-1}$.m$^{-3}$. For this case, runoff=0, Drainage=0, evaporation from surface= **(**Feitosa *et al.,* 2017).

Equation 3 was used for calculation of water use efficiency for every sorghum genotype in all treatments during both seasons SR 2018 and 2020 following Example 1 above.

***Data analysis***

The two season data were statistically analyzed separately season by season using SAS. 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 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 was calculated. Comparing calculated F with F statistic at α = 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 and grain yield with water use efficiency was carried out for each season by plotting a scatter diagram of grain yield (kgha$^{-1}$) against water use efficiency (kg ha$^{-1}$ mm$^{-1}$) for the same treatment. Best fit line was plotted and regression $R^2$ generated.

## Results

***Effect of nitrogen fertilizer application on water use efficiency and yield of sorghum genotypes***

The results on effect of nitrogen fertilizer application on water use efficiency, and yield of sorghum genotypes during SR 2018 and 2020 is shown in Table 3.

The results showed that WUE of sorghum grain and biomass yields were linearly increased by nitrogen fertilizer application at the study site. In SR 2018, application of 6.5 kg N ha$^{-1}$ and 32.5 kg N ha$^{-1}$ significantly increased sorghum WUE from 9.68 to 16.69 biomass kg ha$^{-1}$ mm$^{-1}$ (72%) and from 9.68 to 25.8 kg biomass ha$^{-1}$ mm$^{-1}$ (170%), respectively. WUE measured as grain kg ha$^{-1}$ mm$^{-1}$ was significantly increased by application of 6.5 kg N ha$^{-1}$ and 32.5 kg N ha$^{-1}$ from 3.14 to 5.55 kg ha$^{-1}$ mm$^{-1}$ (77%) and from 3.14 to 9.28 kg ha$^{-1}$ mm$^{-1}$ (196%), respectively. In SR 2020, application of 6.5 kg N ha$^{-1}$ and 32.5 kg N ha$^{-1}$ significantly increased sorghum WUE from 29.35 to 32.8 (12%) and from 29.35 to 36.61 (25%) biomass kg ha$^{-1}$ mm$^{-1}$, respectively. WUE measured as kg ha$^{-1}$ mm$^{-1}$ was significantly increased by application of 6.5 kg N ha$^{-1}$ and 32.5 kg N ha$^{-1}$ from 11.46 to

13.39 kg ha$^{-1}$ mm$^{-1}$ (17%) and from 11.46 to 15.45 kg ha$^{-1}$ mm$^{-1}$ (35%), respectively

**Table 3**

*Effect of nitrogen fertilizer on water use efficiency and yield parameters of sorghum genotypes grown in semi-arid Machakos during short rains 2018 and 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$^{-1}$ | |
| | 2018 | 2020 | 2018 | 2020 | 2018 | 2020 | 2018 | 2020 | 2018 | 2020 | 2018 | 2020 |
| (0 kg N )ha$^{-1}$ | 9.68$^{c}$ | 29.35$^{c}$ | 3.14$^{c}$ | 11.46$^{c}$ | 0.314$^{c}$ | 1.146$^{c}$ | 803$^{c}$ | 3155$^{c}$ | 1697$^{c}$ | 4929$^{c}$ | 2503$^{c}$ | 8086$^{c}$ |
| (6.5 kg N )ha$^{-1}$ | 16.69$^{b}$ | 32.8$^{b}$ | 5.55$^{b}$ | 13.39$^{b}$ | 0.555$^{b}$ | 1.339$^{b}$ | 1436$^{b}$ | 3688$^{b}$ | 2887$^{b}$ | 5350$^{b}$ | 4323$^{b}$ | 9038$^{b}$ |
| (32.5 kg N)ha$^{-1}$ | 25.8$^{a}$ | 36.61$^{a}$ | 9.28$^{a}$ | 15.45$^{a}$ | 0.928$^{a}$ | 1.545$^{a}$ | 2396$^{a}$ | 4256$^{a}$ | 4291$^{a}$ | 5832$^{a}$ | 4692$^{a}$ | 10088$^{a}$ |
| GM | 17.39 | 32.92 | 5.99 | 13.43 | 0.599 | 1.343 | 1545 | 3972 | 2959 | 5590 | 4502 | 9563 |
| CV | 27 | 7.1 | 29 | 7.2 | 29 | 0.72 | 24 | 5.8 | 24 | 9.7 | 27 | 6.1 |
| $r^2$ | 0.86 | 0.97 | 0.86 | 0.98 | 0.86 | 0.98 | 0.93 | 0.99 | 0.92 | 0.95 | 0.86 | 0.98 |
| LSD($p \leq 0.05$) | 0.86 | 1.15 | 0.2 | 0.48 | 0.02 | 0.048 | 59 | 117 | 111 | 277 | 148 | 300 |

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

***Relationship between sorghum yield and WUE***

Results of simple regression of sorghum mean total dry matter yield and grain yield visa-vice water use efficiency at Katumani Machakos is shown in Figure 2

The results show that, total dry matter (TDM) yield of sorghum genotypes obtained in semi-arid machakos were linearly positively 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. Similarly sorghum grain yield was significantly correlated ($r^2$=0.9) to the water use efficiency.

***Water use efficiency of selected sorghum genotypes***

Results on water use efficiency of selected sorghum genotypes from semi-arid regions in the country that were grown in Katumani, Machakos are shown in Table 4. The results show that six and one sorghum genotype had significantly ($p \leq 0.05$) higher water use efficiency (biomass kgha$^{-1}$mm$^{-1}$) in SR 2018 and SR 2020, respectively. Only two sorghum genotypes (*Kitaa kya Ivui* A6 (Andrew Malai) and *Kitui Rasta* A4 (Malia Musomba) had significantly ($p \leq 0.05$) higher water use efficiency (grain kgha$^{-1}$mm$^{-1}$) in both seasons. In SR 2018, *Kitaa kya Ivui* (A6 Andrew Malai), *Kitui Rasta* (A4 *Malia Musomba*), *Kilifi* local (A7 197), *Siaya Ochuti* (A9), *Siaya Nyaktos* A5 (177) (and *Taita Taveta local* A10 (150) were found to be significantly superior in rain water utilization based on biomass production per mm rainfall (biomass kg $ha^{-1}mm^{-1}$) in comparison to Gadam sorghum which is recommended for growing in semi-arid lands in the country. Only *Kitaa kya Ivui* A6 (Andrew Malai) had significantly higher WUE (biomass yield $kgha^{-1}mm^{-1}$) than the check in SR 2020. When WUE was expressed as grain kg $ha^{-1}$ $mm^{-1}$, only two sorghum genotypes (*Kitaa kya Ivui* (A6 Andrew Malai) and *Kitui Rasta* (A4 *Malia Musomba*) were found to have significantly higher WUE than recommended Gadam sorghum variety for semi-arid lands in the country. Three sorghum genotypes (Rhoda Wayua A2 (*Kivila Kya Ivui*), Embu local V A8 (198) and *Siaya Ngware* A1 (191) had similar WUE as the check in SR 2018. In SR 2020, *Kilifi local* V A7 (197), Rhoda Wayua A2 (*Kivila Kya Ivui*), *Siaya Nyaktos* A5 (177) had similar WUE as the check.

**Figure 2**

*Simple regression analysis of (a) mean sorghum TDM and (b) grain yield ($kgha^{-1}$) vs mean water use efficiency at Katumani, Machakos during SR 2020 and 2018*

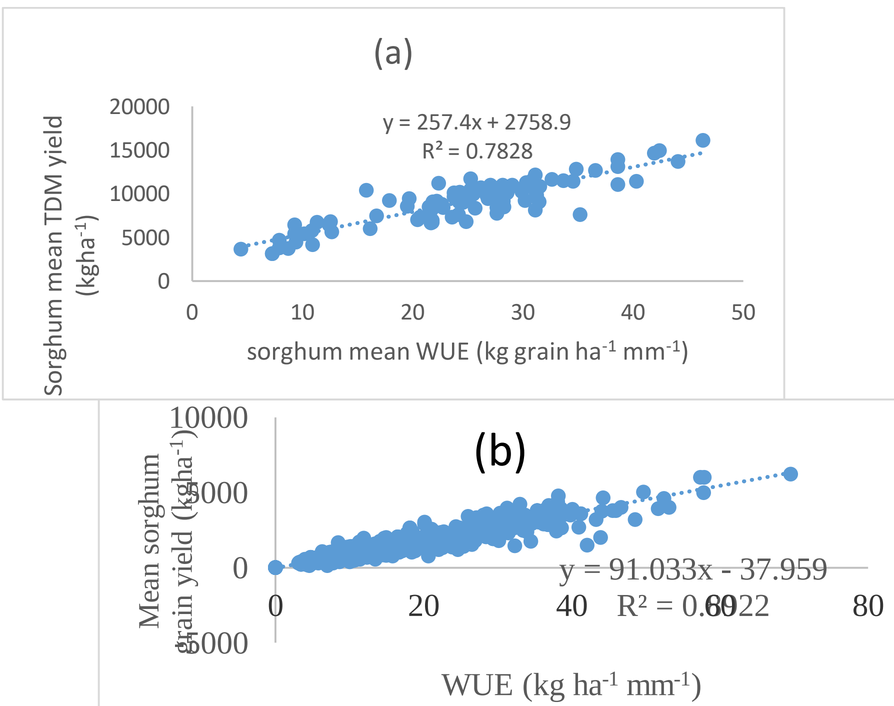


**Table 4**

*Water use efficiency of selected sorghum genotypes from semi-arid grown at Katumani, Machakos during short rains 2018 and 2020*

| Genotypes | Water use efficiency (WUE) | | |
|---|---|---|---|
| | Biomass $kgha^{-1}mm^{-1}$ | Grain kg $ha^{-1}mm^{-1}$ | Grain $kgha^{-1}m^{-3}$ |

| | 2018 | 2020 | 2018 | 2020 | 2018 | 2020 |
|---|---|---|---|---|---|---|
| *Kitaa kya Ivui* A6(Andrew Malai) | 33.3$^{a}$ | 47.61$^{a}$ | 11.8$^{a}$ | 19.90$^{a}$ | 1.18$^{a}$ | 1.990$^{a}$ |
| *Kitui Rasta* A4(Malia Musomba) | 31.4$^{a}$ | 40.30$^{b}$ | 11.9$^{a}$ | 18.71$^{ab}$ | 1.19$^{a}$ | 1.871$^{ab}$ |
| *Kilifi local* V A7(197) | 27.1$^{bcd}$ | 38.74$^{bc}$ | 9.2$^{cdef}$ | 14.68$^{bcd}$ | 0.92$^{cdef}$ | 1.468$^{bcd}$ |
| Rhoda Wayua A2 (*Kivila Kya Ivui*) | 18.0$^{xyz}$ | 36.19$^{bc}$ | 7.9$^{lm}$ | 14.38$^{cd}$ | 0.79$^{lm}$ | 1.438$^{cd}$ |
| Gadam check A11 | 21.0$^{lmn}$ | 34.94$^{bcd}$ | 8.6$^{def}$ | 11.79$^{cde}$ | 0.86$^{def}$ | 1.179$^{cde}$ |
| *Siaya Nyaktos* A5 (177) | 24.7$^{ghi}$ | 33.99$^{bcd}$ | 7.2$^{opq}$ | 15.75$^{abc}$ | 0.72$^{opq}$ | 1.575$^{abc}$ |
| *Embu local* V A8 (198) | 24.0$^{kl}$ | 32.44$^{de}$ | 7.8$^{lm}$ | 12.54$^{cde}$ | 0.78$^{lm}$ | 1.254$^{cde}$ |
| *Siaya Ochuti* A9 | 26.3$^{fgh}$ | 28.75$^{de}$ | 9.0$^{efg}$ | 14.25$^{cde}$ | 0.90$^{efg}$ | 1.425$^{cde}$ |
| *Kitui Rasta* A3 (116)(Mary Mbisu) | 17.9$^{xyz}$ | 28.56$^{de}$ | 7.0$^{opq}$ | 10.17$^{e}$ | 0.70$^{opq}$ | 1.017$^{e}$ |
| *Taita Taveta local* A10 (150) | 26.2$^{fgh}$ | 23.80$^{f}$ | 9.0$^{efg}$ | 11.06$^{de}$ | 0.90$^{efg}$ | 1.106$^{de}$ |
| *Siaya Ngware* A1 (191) | 23.3$^{lmn}$ | 16.8$^{F}$ | 9.2$^{def}$ | 4.52$^{f}$ | 0.92$^{def}$ | 0.452$^{f}$ |
| GM | 17.4 | 32.92 | 5.99 | 13.43 | 0.599 | 1.343 |
| CV | 21 | 7.1 | 25 | 7.2 | 25 | 0.72 |
| $r^2$ | 0.94 | 0.97 | 0.93 | 0.98 | 0.93 | 0.98 |
| l.s.d ($p \leq 0.05$) | 3.5 | 6.7 | 1.4 | 4.2 | 0.14 | 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.

**Discussion**

***Effect of nitrogen fertilizer 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 by 12 and 25% biomass production per mm of rainfall in short rains 2020 and 17 and 35% grain production per mm of rainfall in the same season. In SR 2018, application of 6.5 kg N ha$^{-1}$ and 32.5 kg N ha$^{-1}$ significantly increased WUE of sorghum genotypes by 72 and 170% biomass ha$^{-1}$mm$^{-1}$ and 77 and 196% grain ha$^{-1}$mm$^{-1}$ respectively. The results agree with the findings of Ajeigbe *et al.*, (2018) in semi-arid Sudan savanna zone in Nigeria where they found WUE of sorghum genotypes increased by 48-55% at BUK and 54-76% at Manjibir due to 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 show that, sorghum responds well to nitrogen fertilizer application (Sigua *et al.*, 2018; Gebremariam and Assefa, 2015; Kaizzi *et al.*, 2012) and response is enhanced by availability of moisture in the soil (Yu and Zhao, 2022; Kathuli *et al.*, 2017) and this explains why WUE increase due N fertilizer application was higher in both seasons. These results can be generalized beyond Katumani to other semi-arid regions provided seasonal rainfall, daily temperatures, and soil conditions are similar. 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 and 376.7 mm) received in SR 2020 and 2018 seasons respectively. This explains why farmers grow sorghum genotypes with similar WUE as the check (Gadam) in semi-arid regions. The observation that when rainfall is adequate in semi-arid lands more sorghum genotypes (*Kitaa kya Ivui* (A6 Andrew Malai), *Kitui Rasta* (A4 *Malia Musomba*), *Kilifi* local (A7 197), *Siaya Ochuti* (A9), *Siaya Nyaktos* A5 (177) and *Taita Taveta local* A10 (150) were found to be significantly superior in rain water utilization based on biomass production per mm rainfall (biomass kg ha$^{-1}$mm$^{-1}$) in semi-arid Machakos in comparison to

Gadam sorghum. Sorghum productivity is enhanced by rainfall which increases nitrogen fertilizer response in semi-arid regions (Yu and Zhao, 2022; Kathuli *et al.,* 2017).

***Relationship between sorghum yield and WUE***

Mean sorghum total dry matter yield was significantly correlated ($r^2$ = 0.8) to mean sorghum genotype water use efficiency in SR 2020 implying that in semi-arid lands, sorghum with large TDM yields have large water use efficiency and are more drought tolerant than sorghum genotypes with low TDM yields.

Further regression of sorghum genotypes grain yields and WUE showed a significant correlation ($r^2$=0.9). This showed that sorghum genotypes with large grain yields in semi-arid lands are adaptable to drought and have large WUE. This criterion 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 concur 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 concur with the findings of Hatfield and Dold (2019) that crop biomass or grain yield is correlated to water use efficiency and maximum sorghum grain and biomass. In that study twice irrigated sorghum had higher WUE than once irrigated sorghum (Mahinda *et al.,* 2018). The relationship of mean sorghum total dry matter yield and WUE implies that higher yielding genotypes are drought resilient, efficiently use water, and are adaptable to drought conditions.

***Water use efficiency of selected sorghum genotypes***

The results revealed that six sorghum genotypes (*Kitaa kya Ivui* (A6 Andrew Malai), *Kitui Rasta* (A4 *Malia Musomba*), *Kilifi* local (A7 197), *Siaya Ochuti* (A9), *Siaya Nyaktos* A5 (177) and *Taita Taveta local* A10 (150) were significantly superior in rain water utilization based on biomass productivity per mm rainfall (biomass kg $ha^{-1}mm^{-1}$) in comparison to Gadam sorghum. Sorghum productivity is enhanced by rainfall which increases nitrogen fertilizer response in semi-arid lands (Yu and Zhao, 2022; Kathuli *et al.,* 2017). However, 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)

These genotypes had 4-36% more water use efficiency than recommended Gadam sorghum variety at Katumani, 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 $ha^{-1}$ $mm^{-1}$ (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 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 kg$ha^{-1}mm^{-1}$ at *Manjibir* and 4.4-12.9 kg$ha^{-1}mm^{-1}$ 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. These results disagree with the hypothesis that water use efficiency of sorghum genotypes is not significantly affected by soil nitrogen. 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 concur 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. The implications of the results are 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.

## Conclusion

Nitrogen application at 6.5 and 32.5 kg N $ha^{-1}$ significantly increased WUE of sorghum genotypes in semi-arid Machakos by 12 and 25% on biomass and 17and 35% grain production kg $ha^{-1}$ $mm^{-1}$ of rainfall in SR 2020 and 72 and 170% on biomass and 77% and 196% grain production $ha^{-1}$ $mm^{-1}$ in SR 2018. There are six 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), *Siaya Nyaktos* A5 (177) and *Taita Taveta local* A10 (150) with significantly large grain yield and WUE than Gadam and are recommended to farmers and incorporation in breeding programme for development of water efficient drought resistant sorghum. Sorghum genotype total dry matter yield and grain yield in semi-arid regions are significantly correlated to WUE of sorghum and can be used as indicator of drought tolerant sorghum selection in the region.

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