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Research Article

Productivity and Water Use Efficiency of Sorghum [*Sorghum bicolor* (L.) Moench] Grown under Different Nitrogen Applications in Sudan Savanna Zone, Nigeria

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Nitrogen (N) is an essential nutrient for sorghum growth and development but often becomes limiting due to low availability and loss. The effects of N fertilization on water use efficiency (WUE) and physiological and yield traits of sorghum were investigated in two locations over two cropping seasons (2014 and 2015) in the Sudan Savanna zone of Nigeria. Three sorghum varieties were evaluated under six (6) N-levels (0, 20, 40, 60, 80, and 100 kg ha^{-1}) at a constant phosphorus and potassium level of 30 kg ha^{-1}. Results showed that N increased grain yield by 35–64% at the Bayero University Kano (BUK) and 23–78% at Minjibir. The highest mean grain yield in the N-fertilizer treatments (2709 kg ha^{-1} and 1852 kg ha^{-1} at BUK and Minjibir, resp.) was recorded at 80 kg N ha^{-1}. ICSV400 produced the highest mean grain yields (2677 kg ha^{-1} and 1848 kg ha^{-1} at BUK and Minjibir, resp.). Significant differences were observed among the N-levels as well as among the sorghum varieties for estimated water use efficiency (WUE). The highest mean value coincided with the highest mean grain yield at an optimum application rate of 80 kg ha^{-1}. N-fertilizer treatments increased WUE by 48–55% at BUK and increased WUE by 54–76% at Minjibir over control treatment. Maturity and physiological trait have a significant effect on WUE. The extra early maturing variety (ICSV400) recorded the highest mean WUE while late maturing variety (CSR01) recorded the lowest WUE.

1. Introduction

Nigeria is the largest sorghum (*Sorghum bicolor* L. Moench) producing country in West and Central Africa region, accounting for about 23% of the sorghum production in Africa in 2016 [1]. The country produced 8.5 million tons in 2008, 9.3 million tons in 2009, and 10.0 million tons in 2010 with a projection of being the largest sorghum grain producer in the world [2] by 2020. Sorghum was cultivated on about 10.845 million hectares in 2014 [3], representing about 50% of the total area under cereal crop production and about 13% of the total arable land in the country. Sorghum is typically grown under rain-fed conditions in regions where water and soil fertility are main factors limiting yield [4]. Suboptimal availability of water for unrestricted plant growth and transpiration, that is, drought, is a major limitation to agricultural production [5]. However, sorghum has been found to transform the available water more efficiently into dry matter than most other C_4 crops (e.g., maize) [6]; and the crop is able to utilize water from as deep as 270 cm soil depth [7].

The average grain yield of sorghum in farmers' field is estimated little below 1000 kg ha^{-1} because little or no external inputs are applied [8]. This has led to a decline in soil nitrogen resulting in low yield obtained, food insecurity, nutrient mining, and environmental degradation [8, 9]. Studies by [10–12] on soil test reported that N and P are very low for most dryland areas of Nigeria especially the sorghum growing Sudan Savanna zone. Loss of organic matter, whether by erosion or leaching, adds to the impoverishment of soil resources of several elements essential for plant growth [13]. Sorghum is known for being nutrient-use efficient and managed with lower fertilizer rates compared to maize and rice, but yields can be increased with adequate fertilizer applications [11, 14]. The use of inorganic fertilizers to boost yields of sorghum has been found to increase growth performance, as well as the chemical properties of soil [15]. In the Savanna region of Nigeria where sorghum is cultivated, nitrogen (N) is the most limiting nutrient in soil [12] and a considerable amount of soil-available N is released with the onset of rains but its uptake by crops is insignificant due to the low N requirements of plants at early growth stages [10]. As a result, much of this N is lost through leaching. Therefore, in order to maintain a positive nutrient balance, nutrient inputs from chemical fertilizers are needed to replace nutrients which are exported or lost due to leaching. Although N plays a very important role for good growth and development of sorghum, overfertilization is often harmful as it results in lower yields [16] and negative effect on soil properties. Optimum amounts of N-fertilizer combined with other input factors play a significant role in yield and overall quality of sorghum products. The optimum amount of fertilizer is related to maximum efficiency of production [17].

Consequently, N deficiency results in decreased crop photosynthetic assimilation and seed growth [18, 19]. Studies carried out by [20, 21] found that yield parameters such as plant height, tiller number, panicle number, and number of panicle per m^2 were influenced significantly by complementary application of nitrogen fertilizer on sorghum compared to application of organic fertilizer. A report by [22] also indicated that variation in leaf photosynthetic capacity for varieties, age of leaves, and growth conditions can be attributed to differences in leaf N content. In Nigeria, sorghum is traditionally a food crop grown by subsistence farmers; however, in recent years there are concerted efforts by the government as well as renewed interest by the agro-allied industry as a substitute for imported wheat and barley in the food and beverage industry [2] and call for agricultural scientists and extensions to increase its production and productivity. This has led to the release of 6 open pollinated varieties and 4 hybrids by both public and privately sponsored breeding programs [23] and the encouragement of commercial sorghum production pushing sorghum cultivation into marginal land with lower soil fertility and moisture availability. It is therefore necessary to review the nutrient needs, especially N of some of these varieties and their water use efficiency on marginal land.

2. Materials and Methods

2.1. Description of the Experimental Sites. The experiment was conducted during the 2014 and 2015 growing seasons at two locations within the Sudan Savanna region of Nigeria. The first location was in the ICRISAT research field situated within the Institute for Agricultural Research (IAR) station, Wasai Village, Minjibir (Latitude 12.17°N and Longitude 8.65°E), otherwise known as Minjibir. The second location was at the Bayero University Kano (BUK) Teaching and Research Farm (Latitude 12.98°N and Longitude 9.75°E), otherwise known as BUK. Weather information was collected from Accu Weather Stations installed in the trial sites.

Experimental Design. The experimental design was a split plot arrangement with four replications. The treatments included the six nitrogen fertilizer levels and three sorghum varieties. Six N application rates of 0, 20, 40, 60, 80, and 100 kg ha^{-1}, respectively, were applied as main plots while three sorghum varieties which include ICSV400, CSR01, and local (Kaura) varieties were considered as subplots. The fertilizer treatments were applied in the form of NPK where N-levels varied from 0 to 100 kg ha^{-1} at 20 kg interval, while P_2O_5 and K_2O were applied at a constant rate of 30 kg each per hectare. The gross size of each plot was 15 m^2 which consisted of four ridges spaced at 75 cm apart and sowing was done at 30 cm between plants that gave a total plant population of 44,444 hills ha^{-1}.

2.2. Field Management, Data Collection, and Analysis. The field was disc-harrowed and ridged at 75 cm ridges inter-row spacing before planting. The first cropping season was sown on the 19th of July at BUK and 7th of July at Minjibir in 2014; meanwhile, the second cropping season was on the 20th of July at BUK and 4th of July at Minjibir in 2015. Sowing was done after the rainfall establishment, 5–7 seeds per hole at a depth of 3–5 cm, and thinned to 2 plants per hill at 2 weeks after planting (WAP). For maintaining the optimum plant population, gap filling was done at 8–10 days after planting. The first fertilizer doses (full doses of P, K and half dose of N/plot) were applied by drilling method at sowing, while the second dose was applied at 3 WAP. Weeding was done manually to keep the field weed free. At both locations, measurements including leaf chlorophyll contents (at 3, 6, and 9 WAP) using a SPAD-502 portable chlorophyll meter (Minolta, Tokyo, Japan) were taken. All chlorophyll meter readings were taken midway between the stalk and the tip of the leaf. Leaf area index (LAI) at 6, 9, and 12 WAP (LAI) was measured with Accupar LP-80 portable canopy analyzer. Also, days to 50% flowering, days to 85% maturity, and plant height (cm) were recorded on five randomly selected plants at maturity by measuring the height from the ground to the tip of the panicle. Grain and Stover yields were measured from harvested two rows at the center of each plot [7.5 m^2 area (5 m × 1.5 m)]. Both panicle grain and Stover were sun-dried for 2 weeks before threshing. Grain yield (kg ha^{-1}) and 1000-seed weight (g) were determined while harvest index (HI) was computed as a ratio of grain yield (GY) to the total aboveground dry matter (TDM) on a sun-dried weight basis. All the data were subjected to analysis of variance (ANOVA) using GENSTAT analytical tool (14th edition). Year, N-fertilizer levels, and variety were taken as factors to determine level of significance at 5% probability. Fisher's least-significant difference (LSD) test were computed where the F values were significant at the $P = 0.05$ level of probability [24].

2.3. Water Requirement and Water Use Efficiency under Different N Application. The estimation of crop water requirements during growing seasons was determined from the crop evapotranspiration (ET_c) that was calculated by reference evapotranspiration (ET_0) and recommended crop coefficient

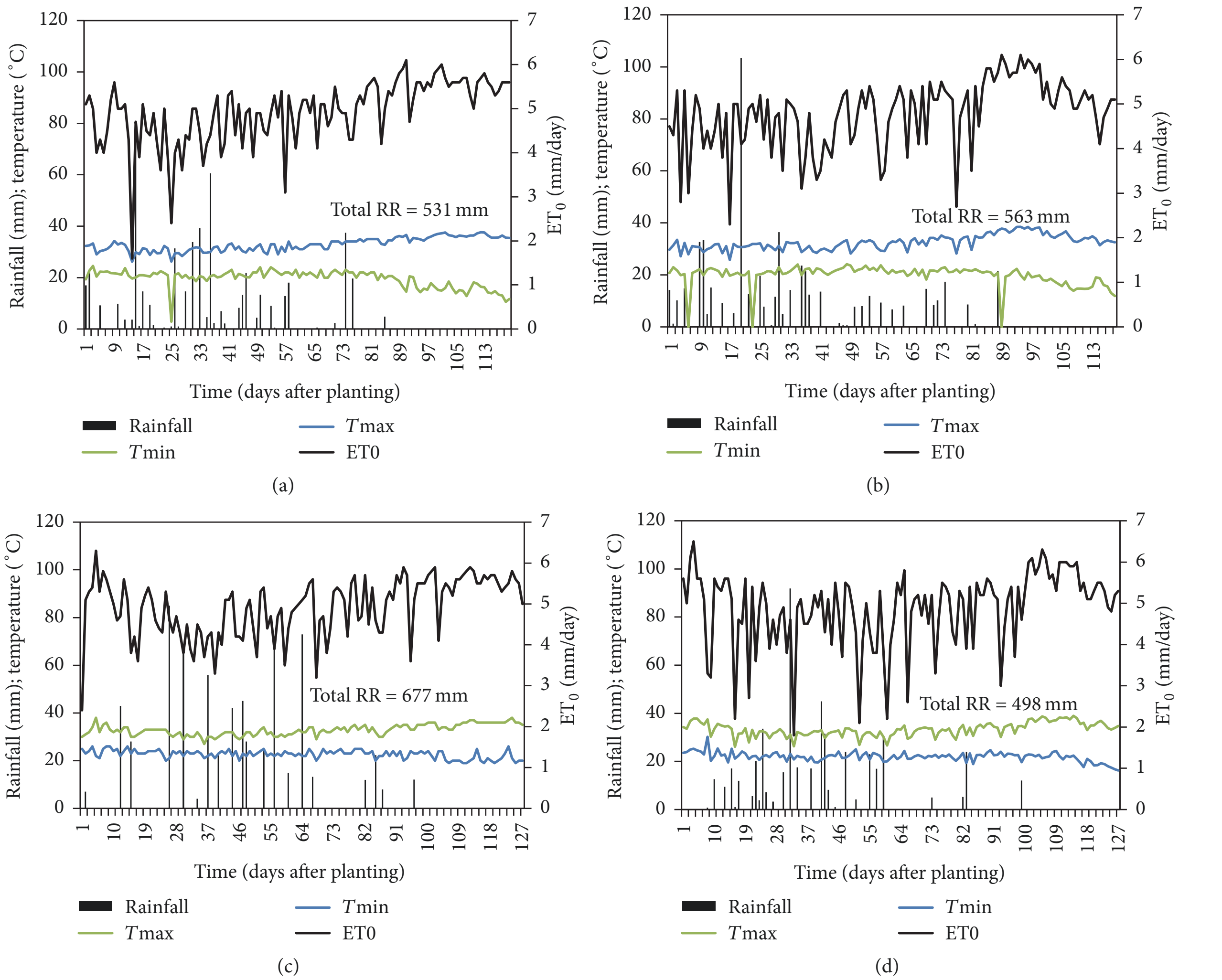

Figure 1: Calculated daily reference evapotranspiration (ET_0), minimum temperature (T_{min}), maximum temperature (T_{max}), and rainfall during the growing seasons of (a) BUK, 2014; (b) BUK, 2015; (c) Minjibir, 2014; and (d) Minjibir, 2015.

(K_c) for sorghum in (1) (Figure 1) [25]. The Penman-Monteith equation was used to calculate reference evapotranspiration (ET_0) in (2); the variables of this equation were described in FAO Irrigation and Drainage Paper No. 56 [26]. The method is of quite good accuracy and is usually used for calculations of evapotranspiration from farmlands.

$$ET_c = K_c ET_0, \tag{1}$$

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(900/\left(T + 273\right)\right) u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34 u_2\right)}, \tag{2}$$

where

ET_0 is reference evapotranspiration [mm day^{-1}],

R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}],

G is soil heat flux density [MJ m^{-2} day^{-1}],

T is air temperature at 2 m height [°C],

u_2 is wind speed at 2 m height [m s^{-1}],

e_s is saturation vapour pressure [kPa],

e_a is actual vapour pressure [kPa],

$e_s - e_a$ is saturation vapour pressure deficit [kPa],

D is slope vapour pressure curve [kPa °C^{-1}],

γ is psychrometric constant [kPa °C^{-1}].

The FAO Penman-Monteith equation determines the evapotranspiration from the hypothetical grass reference surface and provides a standard to which evapotranspiration in different periods of the year or in other regions can be compared and to which the evapotranspiration from other crops can be related. However, actual field evapotranspiration (ET_c) obtained from (1) was used to calculate water use efficiency (WUE) in (3). Water use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration and soil evaporation (evapotranspiration). Water use efficiency was calculated for aboveground biomass at physiological maturity and grain

Table 1: Physical and chemical properties of the soils (0–20 cm depth) at the experimental sites.

Parameters	BUK		Minjibir	
	2014	2015	2014	2015
Soil texture	Sandy loam	Sandy clay loam	Sandy loam	Sandy clay loam
Soil pH value (1 : 2.5 soils : water)	4.86	5.98	5.01	5.75
EC (1 : 2.5 soils : water) (dS/m)	0.083	0.065	0.031	0.035
Soil organic carbon (%)	0.417	0.339	0.196	0.210
Total nitrogen (mg/kg)	311.5	700	163.3	1050
Available P (mg/kg)	2.0	2.612	4.0	3.358
Available K (cmol/kg)	0.396	0.379	0.346	0.390

yield at harvest maturity, using the following equations by [27].

$$\mathrm{WUE} = \frac{Y}{\mathrm{ET}_c}, \quad (3)$$

where

Y is grain yield (kg ha^{-1}),

ET_c is crop evapotranspiration (mm).

2.4. Nitrogen Use Efficiency. The nitrogen use efficiency (NUE), in terms of agronomic efficiency (AE), was calculated as per the following formula [28] and reported as kg grain/kg nutrient (NPK) applied.

$$\mathrm{NUE} = \frac{Y_f - Y_c}{N_a}, \quad (4)$$

where Y_f is grain yield (kg ha^{-1}) in fertilized plot; Y_c is grain yield (kg ha^{-1}) in control plot; N_a is nutrient (N + P_2O_5 + K_2O) applied (kg ha^{-1}).

3. Results and Discussion

3.1. Soil, Weather Variables, and Crop Evapotranspiration Effects on Yield Productivity. The locations were characterized by erratic and poorly distributed mono-modal rainfall pattern. Most of the rains came as short-duration, high-intensity storms between June and September out of which 70% of the total rainfall were received between July and August. In Minjibir, a total rainfall of 677 mm was received in 2014 and 493 mm in 2015 growing seasons while, in BUK, a total rainfall of 531 mm was received in 2014 and 563 mm in 2015 growing seasons. Mean monthly temperatures during the growing season ranged between 26 and 33°C. The soil of the experimental sites is characterized as sandy loam to sandy clay in texture with 0–20 cm depth and pH 4.86–5.98 indicating acidic, low in organic carbon, and nitrogen content varied from 183 kg ha^{-1} to 1179 kg ha^{-1} while available phosphorus varied from low to medium. A detail of the physical-chemical properties of the experimental sites is presented in Table 1.

The total rainfall recorded is within the crop water requirement for sorghum under semiarid conditions (450–650 mm) [29]. In Savanna zone of Mali, it was reported [30] that 11°C and 38°C are the lower and upper temperature threshold limit for sorghum. The present study agreed closely to both upper and lower temperature or base thresholds for the varieties used in both locations. The minimum and maximum temperatures obtained in the present study sites neither exceeded, nor went below sorghum growing temperature thresholds during the growing season. Daily crop evapotranspiration (ET_0) varied from 2.3 to 6.1 mm in both seasons at BUK while Minjibir varied from 1.8 to 6.5 mm. ET_0 recorded high value between flowering and maturity which coincided with the end of rainy season in both locations.

3.2. Effects of Nitrogen and Variety on Phenological and Morphological Traits of Sorghum

3.2.1. Days to Flowering and Maturity. There was a significant difference ($P < 0.05$) among N application rates for days to flowering and maturity at BUK while only days to maturity was significant at Minjibir (Table 2). Days to flowering and maturity were found slightly decreased with increased N application rates. Application under different N-rates attained flowering and maturity faster than control treatment (without fertilizer). Treatment with 100 kg N ha^{-1} reached maturation earlier by 3 and 5 days at BUK and Minjibir, respectively, compared to control treatment. Highly significant ($P < 0.001$) differences were observed among the sorghum varieties for flowering and maturity. ICSV400 flowered at 71 days after planting (DAP) followed by a local (85 DAP) and CSR01 (97 DAP), respectively. Also, ICSV400 variety attained physiological maturity at 91 DAP (indicating early maturing variety) while CSR01 and local varieties matured above 100 days in both locations and are therefore grouped as medium maturing varieties. Significant differences were observed between the years for sorghum days to 50% flowering in the 2 locations, though it was only significant for maturity in BUK. The differences in days to flowering could be associated with varietal response to day length (photoperiods) and soil moisture availability especially at Minjibir. The result was in agreement with earlier studied reported by [31]. ICSV400 and local varieties flowered and matured earlier in BUK than Minjibir due to higher fertility status obtained in BUK, while the plants also flowered and matured earlier in the fertilizer plots than the unfertilized plots. This implies that days to flowering and maturity are influenced by inherent

Table 2: Effect of fertilizer levels and variety on phenological and morphological traits of sorghum in Sudan Savanna zone Nigeria.

Treatment	BUK							Minjibir						
	50% flowering	Maturity	SPAD	LAI	SPAD	LAI	Plant height	50% flowering	Maturity	SPAD	LAI	SPAD	LAI	Plant height
	(days)		(3 WAP)		(6 WAP)		(cm)	(days)		(3 WAP)		(6 WAP)		(cm)
Year (Y)														
2014	76.32	106.31	41.90	3.78	48.83	2.84	230.6	88.4	109.5	41.72	2.50	40.18	2.78	201.1
2015	79.76	104.89	38.69	3.27	42.70	2.29	237.9	80.2	108.1	40.07	2.28	37.51	1.68	190.5
P of F	**0.005**	**0.041**	**0.106**	**0.073**	**0.024**	**0.013**	**0.109**	**0.002**	**0.249**	**0.035**	**0.036**	**0.012**	**<0.001**	**0.094**
SED	0.46	0.41	0.99	0.19	1.02	0.19	4.56	0.80	0.42	0.77	0.11	1.04	0.09	6.24
LSD	1.46	1.31	1.40	0.60	1.33	0.33	9.04	2.55	0.83	1.53	0.21	2.07	0.17	12.37
Fertilizer (F)														
0	79.4	107.5	38.8	3.20	40.0	2.46	232.4	84.2	111.7	39.0	1.87	33.9	1.69	180.7
20	78.7	105.5	40.7	3.58	44.6	2.65	218.3	85.0	110.2	40.0	2.23	35.8	2.12	185.0
40	77.6	104.9	41.2	3.62	47.5	2.61	258.2	84.1	108.1	38.5	2.47	37.2	2.11	186.5
60	77.8	105.3	39.8	3.57	45.0	2.46	236.8	84.2	108.8	41.1	2.50	42.0	2.31	209.7
80	77.5	105.7	40.7	3.64	46.8	2.66	233.0	84.0	107.6	44.7	2.65	42.8	2.70	209.2
100	77.3	104.7	40.7	3.53	46.9	2.53	226.8	84.2	106.2	42.1	2.61	41.4	2.46	203.6
P of F	**0.007**	**<0.001**	**0.085**	**0.236**	**0.136**	**0.809**	**<0.001**	**0.792**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.015**
SED	0.64	0.66	0.88	0.20	1.56	0.19	7.90	0.84	0.72	1.33	0.18	1.81	0.15	10.81
LSD	1.28	1.30	1.75	0.39	3.10	0.37	15.66	1.67	1.44	2.65	0.36	3.58	0.30	21.43
Variety (V)														
CSR01	90.4	117.1	40.7	3.99	48.1	3.05	258.4	90.0	124.3	41.2	2.83	38.4	2.55	214.7
ICSV400	64.5	90.65	39.6	2.98	42.3	2.03	167.3	70.7	90.9	39.3	1.88	37.6	1.63	141.5
Local	79.2	109.0	40.6	3.59	46.9	2.61	277.0	85.2	111.1	42.2	2.45	40.6	2.51	231.2
P of F	**<0.001**	**<0.001**	**0.156**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.01**	**<001**	**0.05**	**<0.001**	**<0.001**
SED	0.46	0.46	0.63	0.14	1.10	0.13	5.58	0.60	0.51	0.94	0.13	1.28	0.11	7.64
LSD	0.90	0.92	1.24	0.27	2.19	0.26	11.07	1.18	1.01	1.87	0.25	2.53	0.21	15.15
CV (%)	2.9	2.2	7.6	17.2	11.1	25.5	11.7	3.6	2.3	11.3	26.3	16.1	23.7	19.1
Interaction														
Y × F	*	*	ns	ns	ns	ns	ns	ns	**	**	*	*	**	ns
Y × **V**	**	**	ns	**	**	*	**	**	**	ns	*	ns	**	**
F × **V**	ns	*	*	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns
Y × F × **V**	*	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns

SED: standard error of differences of means; *LSD*: least significant differences of mean (5% level); *CV*: coefficient of variation; ** and * mean significant different at 0.01 and 0.05 level of probability; *ns*: not significant.

soil fertility and drought. The sorghum plants flowered and matured significantly earlier under drought conditions as observed in Minjibir in 2015.

3.2.2. Leaf Chlorophyll Content. Leaf chlorophyll content is a good indicator of photosynthetic capacity of any crop [32]. Low concentrations of chlorophyll limit photosynthetic potential directly and lead to a decrease in biomass production in the plants [32, 33]. Table 2 shows that leaf chlorophyll content (SPAD) varied between years, among N application levels and sorghum varieties. While SPAD values at 3 and 6 WAP were significantly higher in 2014 than 2015 in Minjibir, it was significantly higher only at 6 WAP in BUK. This directly relate to the rainfall which was higher and better distributed in 2014 than 2015 in Minjibir. N-Fertilizer applications did not significantly affect SPAD (leaf chlorophyll content or health of the leaf) readings at 3 and 6 WAP in BUK though significant differences were observed among the fertilizer treatments in Minjibir as well as among the varieties in both locations. The soils in BUK were comparatively higher in nutrients to support the initial demand of the seedlings compared to soils in Minjibir. This was also evident in Minjibir where the leaf chlorophyll content increased with increasing N application rates. Highest SPAD value was recorded at 100 kg N ha^{-1} in BUK and 80 kg N ha^{-1} in Minjibir. While there was no significant differences among the varieties for SPAD readings at 3 WAP in BUK significant differences were observed at 6 WAP and in Minjibir at both 3 and 6 WAP. At BUK, CSR01 recorded the highest values (40.7 at 3 WAP and 48.1 at 6 WAP) compared to local and ICSV400. Slightly lower SPAD values recorded in Minjibir were compared to BUK confirming that BUK had higher fertility than Minjibir.

3.2.3. Leaf Area Index. There were no significant differences among N-fertilizer treatments for leaf area index (LAI) at 3 WAP and 6 WAP in BUK (Table 2) though highly significant differences were observed for LAI at 3 WAP and 6 WAP among the N-fertilizer treatments in Minjibir. The application of 80 kg N ha^{-1} produced significantly higher LAI value at 3 WAP and 6 WAP compared to the control treatment at both locations. At both locations, N-fertilizer increased early seedling vigour with higher LAI values recorded at 3 WAP but slightly decreased at 6 WAP which could be associated with increase in height of the plants compared to biomass. Similarly, reduction of LAI value was also reported in maize and forage maize by [34]. Early seedling vigour may be critical to maximizing uptake and efficient utilization of nutrients. LAI values at 3 and 6 WAP were significantly higher in 2014 than 2015 in Minjibir, though it was significantly higher only at 6 WAP in BUK. The differences in LAI between the two years in Minjibir were due to drought observed in 2015. This effect was also noticed in the plant health (SPAD values) and days to flowering.

Significant differences were also observed among the sorghum varieties in both locations for LAI at 3 and 6 WAP. At BUK, LAI value of 3.99 m^2/m^2 was recorded at highest from CSR01 and the lowest value was obtained from ICSV400 (2.98) at 3 WAP. Meanwhile, at 6 WAP, CSR01 recorded the highest of 3.05 m^2/m^2 and the lowest from ICSV400 (2.03 m^2/m^2). At Minjibir, CSR01 had highest LAI value of 2.83 m^2/m^2 and 2.55 m^2/m^2 at 3 and 6 WAP followed by a local variety, while the lowest value was recorded from ICSV400 (1.88 m^2/m^2 and 1.63 m^2/m^2 at 3 and 6 WAP).

3.2.4. Plant Height. Significant differences were observed among the different N-fertilizer rates as well as among the varieties in both locations for plant height. Increase in fertilizer application rate increased plant height up to 40 kg N/ha in BUK and up to 80 kg N/ha in Minjibir (Table 2). Nitrogen application therefore has a significant positive effect on sorghum growth in the two locations. It is interesting to note that the highest SPAD value as well as sorghum height in Minjibir was observed at 80 kg N/ha. Among the varieties, local control was significantly taller (277 cm) than CSR01 (258 cm) and ICSV400 (167 cm) in BUK. Similar observations were made in Minjibir where the local control was significantly taller (231 cm) than CSR01 (214.7 cm) and ICSV400 (141 cm).

3.3. Effect of N-Fertilizer Levels and Variety on Yield and Yield Components. The effect of different levels of N-fertilizer and varieties on the mean panicle length, 1000-seed weight, grain, and Stover yields in the two locations is presented in Table 3. N-fertilizer levels had no significant effect on panicle length in both locations, but highly significant on varieties with local variety recording the longest panicle (40.7 and 34.7 cm) over CSR-01 (30.7 and 28.1 cm) and ICSV400 (25.3 and 18.47 cm), respectively, at both locations. N-fertilizer application had no significant effect on 1000-seed weight, though there were significant differences among the sorghum varieties for 1000-seed weight. Local variety recorded highest mean value (29.2 g and 2.99 g) in both locations while the lowest value was measured from ICSV400 (22.7 g) in BUK and CSR01 (20 g) in Minjibir. The low 1000-seed weight of CSR01 in Minjibir was as a result of drought observed during the grain filling stage.

Significant differences were found among the N-fertilizer rates and varieties for both grain and Stover yields in the two locations (Table 3). Mean grain yield increased linearly with increase in N-levels across individual variety. The result showed that sorghum grain yields were higher in BUK over Minjibir by 29, 31, and 54% for local, ICSV400, and CSR01, respectively. The highest grain yield observed in BUK than Minjibir could be associated with favourable rainfall distribution, inherent higher soil micronutrients, and high water retention capacity of soil. Both the local and ICSV400 varieties had a comparative yield advantage over CSR01 in the two locations, due to earliness to flowering that coincides with the end of the rainy season for ICSV400 while the local variety possessed drought tolerance trait to complete its growth cycle even after cessation of rainfall. In BUK, N-fertilizer treatments increased yield over control treatment by 30–63% for CSR01, 38–49% for ICSV400, and 36–74% for local variety respectively. Though grain yield recorded low value in Minjibir compared to BUK, the application of N-fertilizer was highly significant. Grain yield was increased by 22–106% for CSR01, 28–96% for ICSV400, and 10–68% for local variety, respectively, over the control treatment. This result was in agreement with those reported by [4, 35] on sorghums under different N-level over Guinea Savanna, Ghana, and the semiarid region of India

N-Fertilizer treatment at 80 kg ha^{-1} produced the highest mean grain yields in BUK and Minjibir (2709 and 1881 kg ha^{-1}, resp.). This was significantly higher than control and 20 kg N/ha. The N-fertilizer rate increased grain yield in the range of 35–64% at BUK and 23–79% at Minjibir over control (no fertilizer) treatment. ICSV400 produced the highest mean grain yield (2677 kg ha^{-1}) over local (2411 kg ha^{-1}) and CSR01 (1902 kg ha^{-1}) varieties at BUK while ICSV400 recorded the highest mean grain (1848 kg ha^{-1}) over local (1693 kg ha^{-1}) and CSR01 (876 kg ha^{-1}) at Minjibir. While there were no significant interactions among the factors for grain yields in BUK, significant interactions were found in Minjibir (Table 3). Table 4 shows the interaction effects of year × fertilizer, year × variety, fertilizer × variety, and year × fertilizer × variety. Grain yield ranged from 440 kg ha^{-1} by CSR01 at 20 kg N-fertilizer application to 3096 kg ha^{-1} by local with application of 80 kgN fertilizer. In 2014, local variety produced significantly higher grain yields across the N-fertilizer levels, which ranged from 1592 kg ha^{-1} at zero fertilizer application to 3096 kg ha^{-1} at 80 kgN (indicating the optimum level) while the CSR01 produced the lowest grain yield at the optimum level application of 80 kgNha. Contrary to the result obtained in 2014, ICSV400 recorded higher grain yield across N-level ranging from 1009 kg ha^{-1}

TABLE 3: Effect of fertilizer levels and variety on panicle length, 1000-seed weight, grain and Stover yields and harvest index of sorghum in Sudan Savanna zone.

Treatment	BUK					Minjibir				
	Panicle length	1000-seed weight	Grain yield	Stover yield	Harvest Index	Panicle Length	1000-seed weight	Grain yield	Stover yield	Harvest index
	(cm)	(g)	($kg\,ha^{-1}$)		(%)	(cm)	(g)	($kg\,ha^{-1}$)		(%)
Year										
2014	34.09	29.38	2318	11435	19.92	26.69	28.53	1844	4580	28.87
2015	30.39	22.95	2342	7020	25.79	27.49	19.75	1101	4044	22.26
P of F	**<0.001**	**<0.001**	**0.873**	**<0.001**	**0.019**	**0.062**	**0.007**	**0.001**	**0.222**	**0.012**
SED	0.87	0.86	78.8	333.7	1.71	0.43	1.30	66	348	1.19
LSD	1.72	1.39	156.2	661.7	5.44	0.84	4.13	209	1108	1.84
Fertilizer (F)										
0	32.91	26.78	1649	5526	26.09	26.76	24.71	1048	3928	21.70
20	34.09	26.17	2231	6267	29.07	27.19	24.33	1288	4127	24.82
40	32.22	26.64	2452	6038	30.20	26.68	23.41	1324	4194	24.85
60	32.00	26.33	2579	6816	29.07	27.37	23.63	1534	4725	25.64
80	30.55	26.17	2709	7557	28.23	27.13	24.60	1881	4542	28.94
100	31.69	24.92	2360	6676	27.73	27.38	24.15	1757	4356	27.42
P of F	**0.286**	**0.459**	**0.001**	**0.030**	**0.148**	**0.893**	**0.790**	**<0.001**	**0.023**	**0.013**
LSD	2.97	1.92	452.1	1149	3.06	1.46	2.40	249.8	476	3.52
Variety (V)										
CSR01	30.70	26.59	1902	7162	22.6	28.11	19.99	876	4738	15.46
ICSV 400	25.33	22.70	2677	5061	36.1	18.47	22.46	1848	3750	33.32
Local	40.71	29.21	2411	7217	26.5	34.68	29.98	1693	4448	27.90
P of F	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
SED	1.06	0.68	131.2	329.7	1.17	0.52	0.86	73.8	232	1.29
LSD	2.10	1.35	266.1	668.7	2.39	1.03	1.70	149.7	463	2.63
CV (%)	16.1	3.6	28.5	17.9	32.7	9.4	17.3	32.7	26.4	23.3
Interaction										
Y × F	ns	ns	ns	ns	ns	*	ns	*	*	ns
Y × V	*	**	ns	*	ns	ns	*	**	ns	**
F × C	ns	ns	ns	ns	ns	ns	ns	*	**	ns
Y × F × V	ns	ns	ns	ns	ns	ns	ns	*	*	**

SED: standard error of differences of means; *LSD*: least significant differences of mean (5% level); *CV*: coefficient of variation; ** and * mean significant different at 0.01 and 0.05 level of probability; *ns*: not significant.

at zero N application to 2212 $kg\,ha^{-1}$ at 60 kgN applied while the lowest grain yield was recorded from CSR01 across the N-level applied. The difference in rainfall amount received (677 mm in 2014 and 489 mm in 2015) could be directly linked to variation in yields recorded across the N-level and among varieties.

Furthermore, N-fertilizer at 80 $kg\,ha^{-1}$ produced significantly higher mean Stover (7557 $kg\,ha^{-1}$) in BUK while 60 $kgNha^{-1}$ produced significantly higher mean Stover (4725 $kg\,ha^{-1}$) in Minjibir than other treatments. N-treatments increased Stover yield by 9–35% at BUK and 5–19% at Minjibir over control treatment. The differences in N-fertilizer optimum rate at both locations could be attributed to initial soil micronutrients and rainfall distribution pattern. Among the varieties, local produced significant higher mean Stover yield (7217 $kg\,ha^{-1}$) than CSR01 (7162 $kg\,ha^{-1}$) and ICSV400 (5061 $kg\,ha^{-1}$) at BUK; meanwhile CSR01 recorded higher mean Stover yield (4728 $kg\,ha^{-1}$) over local and ICSV-400 at Minjibir. High grain yields of sorghum obtained with increased rates of N-fertilizer can be attributed to the significant increase in the yield components, namely, a number of grains/panicle and 1000-grain weight, which corroborated the finding reported by [4]. Also, N-fertilizer application rate up to 80 $kg\,N\,ha^{-1}$ had a profound linear effect on grain yield which implies that optimum N application rates for sorghum are 80 $kg\,N\,ha^{-1}$; further increased N rate did not increase grain yield proportionately. In addition, Stover yield increased with N rates as would be expected because higher

Table 4: Effects of year, N-fertilizer, and variety on sorghum grain yield Minjibir.

Treatment	2014				2015			
	CSR01	ICSV400	Local	Mean	CSR01	ICSV400	Local	Mean
0	701	1424	1592	1239	489	1009	1074	857
20	1250	1703	1965	1639	440	1428	944	937
40	897	1856	2283	1679	564	1425	919	969
60	1379	1978	2120	1826	606	2212	909	1242
80	1434	2760	3096	2430	1013	1599	1387	1333
100	1082	2627	3040	2250	657	2149	989	1265
Grand mean	1472							
LSD (Y × F)	307							
LSD (Y × V)	352							
LSD (F × V)	222							
LSD (Y × F × V)	500							

N-levels might have accelerated the conversion of rapidly synthesized carbohydrates (owing to increased N supply) into protein and developed a plant root system faster as reported by [36]. This resulted in early crop growth, which was finally expressed in taller plants, greater biomass yield, and consequently higher grain production. Reference [37] reported that the highest yield was obtained at the N-level of 125 kg ha^{-1} and likened the positive effect of increased N fertilization on dry matter yield to plant height, leaf, and stem dry weight and the amount of tillers increases which leads to the increase in total dry matter yield.

The physiological efficiency of assimilates from source into economic sinks is known as harvest index (HI). The effect N-fertilizer levels on harvest index (HI) were only significant at Minjibir but not significant differences at BUK (Table 3). Similar to observation made by [38], HI increased with increase in N-fertilizer in Minjibir; however, in BUK there was no clear cut response of HI to N-fertilizer rates. At both locations and among the varieties, ICSV400 had the highest mean HI (36.1 and 33.3%) at BUK and Minjibir followed by local variety (26.5 and 27.9%) while CSR01 recorded the lowest mean HI (22.6 and 15.5%) indicating genotypic variations in partitioning efficiency. However, higher HI may be attributed to lower mean biomass recorded while the lower HI could be linked to higher biomass as observed in ICSV400 and CSR01 accordingly. Also, lower mean HI values in this experiment among the varieties might suggest the need for the enhancement of biomass partitioning through genetic improvement.

3.4. Effect of N-Fertilizer Levels on Water Use Efficiency of Sorghums. Water use efficiency (WUE) is one of the most important indices for determining optimal crop-water management practices. Figure 2 shows the effect of N-fertilizer levels on WUE across the varieties. The estimated WUE was not significantly different among the N-treatment at BUK but highly significant effect was observed at Minjibir. In both locations, mean WUE value increased from 0 kgN to 80 kgN and dropped afterwards, though CSR01 and ICSV400 dropped after 60 kgN in Minjibir and BUK, respectively. This result agreed with similar studies reported by [39, 40] that increase in WUE with the increased N-fertilizer levels is likely to be related to the significant increase in total dry matter compared to grain yield alone. N application at 80 kg ha^{-1} estimated significantly higher mean WUE values across the N-treatments and varieties (with exception of ICSV400 at BUK and CSR-01 at Minjibir that recorded the highest WUE at 60 kg N ha^{-1}). Higher mean WUE obtained in ICSV400 implies more efficient water use than the other varieties in both locations, which could be associated with much less transpiration demand from vegetative biomass which enhanced water resources available for grain filling during the reproductive stage. In BUK, the mean WUE ranged from 4.4 to 12.9 kg ha^{-1}mm^{-1} and N-fertilizer treatments increased WUE by 48–55% over the control (no fertilizer) treatment. Meanwhile, at Minjibir, WUE varied from 1.7–11.5 kg ha^{-1}mm^{-1} and N-fertilizer treatments increased WUE by 54–76% over control treatment.

3.5. Effect of N-Fertilizer Levels on Nitrogen Use Efficiency of Sorghums. The effect of N-fertilizer levels on nitrogen use efficiency of sorghum varieties is presented in Figure 3. Nitrogen use efficiency (NUE) is calculated as a ratio of grain yield to the amount of N applied. NUE decreased as a linear function of increasing N-levels, but the estimated values varied between the two locations. This result was in agreement with several studies reported on various crops, for instance, on sorghum [9], millet [41], and maize [42]. The varieties showed significant differences for estimated NUE. In BUK, ICSV400 recorded the mean highest NUE (35.7 kg grain/kg) value, followed by local (30.4 kg grain/kg) and CSR-01 (21.2 kg grain/kg) at 20 kg N ha^{-1} and the value decreased with increased N-level. On the contrary, in Minjibir, local variety recorded the highest NUE (24.4 kg grain/kg^{-1}) with significant differences of more than 10 kg grain/kg^{-1} compared to other varieties at 20 kg N ha^{-1}. Meanwhile, CSR01 had significantly lower NUE than local and ICSV400 varieties across the different N-levels. The differences among sorghum varieties for higher NUE mechanisms could be associated with individual morphological, anatomical, and biophysical traits. This finding was similar to those reported by [4, 43]

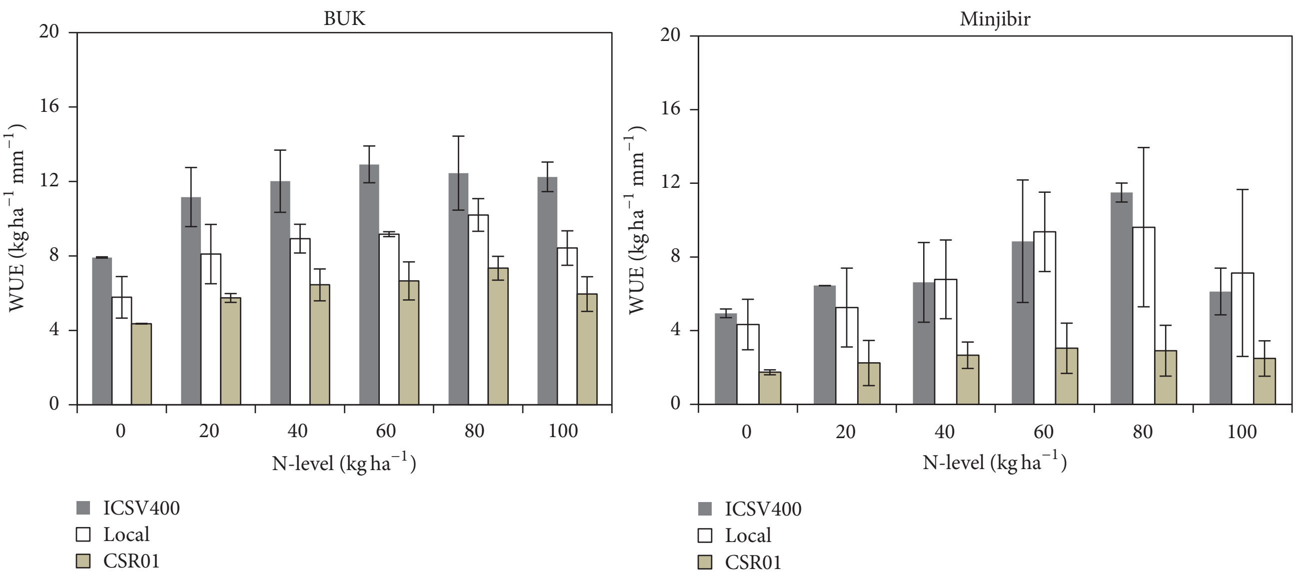

Figure 2: Effects of N-fertilizer rates on water use efficiency (WUE) of selected sorghum varieties in Sudan Savanna zone. *P of F equals 1.000 in BUK and 0.011 in Minjibir*.

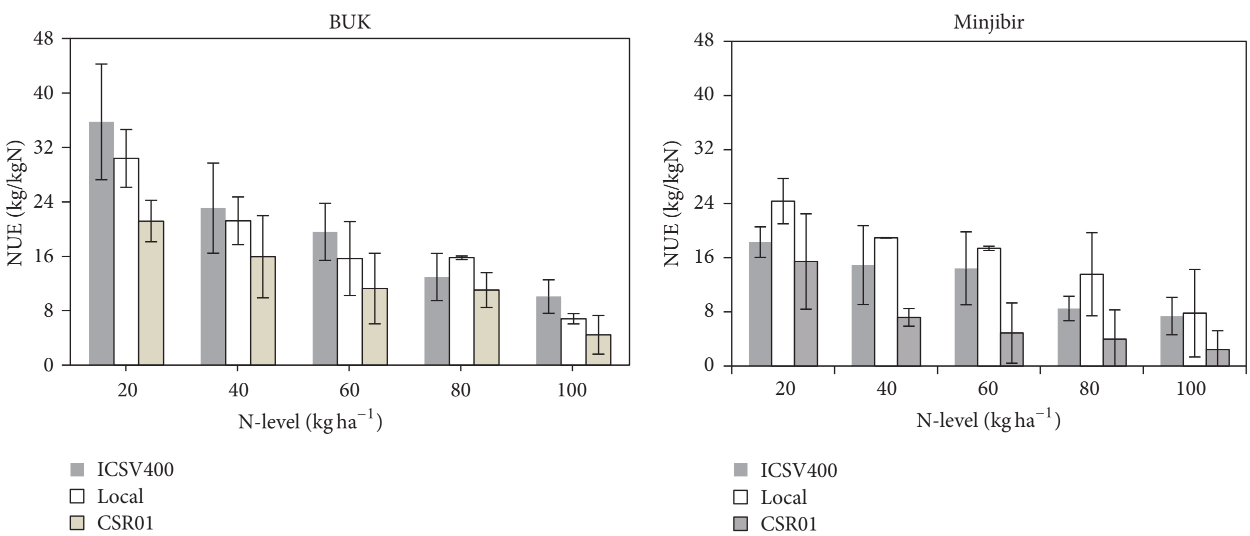

Figure 3: Effects of N-fertilizer rates on nitrogen use efficiency (NUE) of selected sorghum varieties in Sudan Savanna zone. *P of F equals 0.574 in BUK and 0.017 in Minjibir*.

that demonstrated genetic diversity for N use efficiency in grain sorghum. Thus, exploiting these differences in nutrient demand and efficiency is a possible alternative for reducing the cost and reliance upon fertilizer for maximizing yield productivity.

4. Conclusion

It was noted that increase in nitrogen fertilizer applications up to a point led to a significant increase in all parameters of crop growth, yield, and yield components of sorghum in the Sudan Savanna of Nigeria. Inherent soil fertility and rainfall distribution contributed significantly to the grain and Stover yields of sorghum irrespective of fertilizer rates applied. Treatment application at the rate of 80 kg N ha^{-1} was found to be the optimum application rate in both locations, above which no significant differences in grain and Stover yields. Seedling health at 3 weeks after planting was found to have significant correlation with plant height and yields implying that agronomic practices that will ensure excellent seedling vigor and health should be practiced for high grain and Stover yields. The WUE increased with increasing N-fertilizer application rates up to 80 kgN/ha and also significantly different among sorghum varieties. Grain yield was used in estimating the WUE, indicating optimum is reached at 80 kgNha^{-1} in both locations with slight differences among varieties. This implies that increased WUE between N-fertilizer levels could be more strongly associated with total dry matter produced than grain yield. The NUE decreased with increased N-fertilizer level with mean highest value recorded at 20 kg N ha^{-1} at both locations. Across the three varieties, ICSV400 recorded the mean highest NUE (35.7 kg grain/kg) value at BUK and local recorded mean highest value (24.4 kg grain/kg) which decreased with increased N-fertilizer levels.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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