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Full Length Research Paper

Sorghum yield and water use under Phosphorus fertilization applications in the Sudan savanna of Nigeria

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Low soil fertility and water shortage are major constraints to food production and food security in semi-arid environments. Field experiments were conducted during two growing seasons (2014 and 2015) in two locations in Sudan savanna zone of Nigeria. The studyexaminedthe effects of Phosphorus (P) applications oncrop evapotranspiration (ET_c) water use efficiency (WUE)and agronomy phosphorus use efficiency (APUE)and sorghum productivity. The experiments were arranged in split plot design with five (5) P-fertilizerlevels(0, 15, 30, 45 and 60 kg $P_20_5ha^{-1}$) as the main plot and threevarieties (CSR01, ICSV400 and local) as sub-plot in four replications.Results showed significant differences ($P<0.05$) amongthe P levels and sorghum varieties for grain yield in both locations and seasons. P increased grain yield by 19-39% over control treatment.The highest mean yield of 3156 kg ha^{-1} at Minjibir and 2929 kg ha^{-1} at BUK indicate optimum yield was recorded at the 45 kg$P_20_5ha^{-1}$ application rate and significantly higher than P rates at 0, 15 and 30kgha^{-1} respectively.Grain yield WUE washighly significantamongP-fertilizer levels and varieties, however, no significant differences between P-fertilizer rates for biomass WUE.P-application increased grain WUE of sorghum by 20-39%, the ICSV400 estimated the mean highest value of 9.3 and 8.6 kg $ha^{-1}mm^{-1}$ over CSR-01 and local at both locations.The study observed that the application of P could be an effective fertilization strategy to enhance sorghum yield and water use in low-rainfall cropping system and drought prone environment.

Keywords: Biomass WUE, crop evapotranspiration (ET_c), Grain yield WUE, P-Fertilizer effect, sorghum productivity.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) *Moench*] is the fifth most important cereal crop in the world, but first an important cereal in Nigeria. It is themostextensively traditionally grown cereal in the semi-arid of Nigeria extending from the Southern Guinea, to Sahel Savannah of Nigeria, primarily because of its adaptation to drought. The industrial demand for sorghum is growing with several flour mills in the country having started using it or considering it as a substitute for wheat to produce composite flour as well as high energy foods. This is in

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addition to the increasing demand by malting industries for beverages. This development is expected to increase the demand for sorghum by over 30% in coming years.

Although sorghum is an indigenous crop and exceptionally adapted to the region, the yields are generally less than 1.5t/ha (FAO, 2014b). Important factors that contribute to these low yields includes; low inputs, poor soil fertility and the non-availability of improved varieties or hybrids with significant yield superiority over farmers' landrace varieties. With a projection of world food demand expected to be double by the year2050 (Borlaug, 2009), it is important to increase food production with lower water use under nutrient deficit condition (Perry et al.,2009) particularly in a more erratic rainfall pattern being experienced in the regions. Currently, water stress and nutrient deficits are the main factors limiting primary production in semi-arid environments of West Africa (Rockstro and De Rouw, 1997; Zand-Parsa *et al*., 2006). Phosphorus (P)is one of the major essential plant nutrients after nitrogen required by plants for growth and yield productivity and is the second most deficient plant nutrients (Munir *et al.,* 2004;Karikari and Arkorful, 2015). It is, however, one of the most immobile, inaccessible and unavailable nutrients present in soils (Narang *et al.,* 2000). The low P, N and micro-nutrients present in the soil are the major constraints to crop growth and production in nutrients depleted sandy soil of Sub-Saharan Africa (Nyoki and Ndakidemi, 2014). The application of phosphorus fertilizer gradually increased plant height, stem diameter, number of leaves per plant, leaf area per plant and fodder yield (Khalid *et al.,* 2003;Roy and Khandaker, 2010).Das *et al.,* (2008) observed that the response of sorghum to P was strongly influenced by soil P status as well as applied P rate, whichwas similar at three physiological stages of crop growth viz. boot leaf initiation, 50% flowering and maturity.However, balancing the P rate, water use efficiency (WUE) and yield is an important problem in dryland farming systems. Better understanding of interactions among precipitation, fertilization and crop production is essential for efficient utilizations of water resources and sustainable food productions in rain-fed cropping systems experiencing climate change (Fan et al., 2005;Nkaa *et al.,* 2014). One of the options of reducing low yields due to soilP content is to determine the best level of P application so as to increase yield and returns fromsorghum.Tardieu, (2013) reported that environmental conditions greatly affectWUE.Blum, (2005;2009) found that WUE is higher in regions with wet air, and that crops that are grown during rainy seasons have ahigher WUE than those grown during dry seasons and also large differences exist between crops.WUE is higher in C_4 crops, such as maize, sorghum, or millet, than in C_3 crops.WUE decreases when evaporative demand increases, because transpiration is higher at high evaporative demands for a given photosynthesis.Thus, this study examined the effects of P-fertilization on growth, yields, crop evapotranspiration ($ET_{c)}$ and WUE, of three contrasted water-sensitive sorghums in Sudan Savanna zone of Nigeria. Specically to examine; (i) the effects of P-fertilization onsorghum growth and productivity, ET_c, WUE and agronomic phosphorus use efficiency (APUE) and (ii) establish relationships among crop yield, WUE and ET and determine optimum P-fertilizer rates in the Sudan savanna zone of Nigeria.

MATERIAL AND METHODS

Description of the experimental sites

The experiments were conducted during the 2014 and 2015 growing seasons on a predominantly sandy loam soil at two locations within the Sudan savanna zone of Nigeria. The first location (Minjibir) was ICRISAT Research field situated within Institute for Agricultural Research, Ahmadu Bello University, Zaria, in Wasai village, Minjibir Local Government Area, Kano State (Latitudes 12.17°N and longitude 8.65°E). The second location (BUK) was Bayero University Kano, Teaching and Research Farm (Latitude 12.98°N and Longitude 9.75°E). Soils of the experimental sites were characterized as sandy loam to sandy clay in texture at 0-20 cm depth, pH 4.86 – 5.98 indicating acidic, low in organic carbon and Nitrogen content varied from 157.2 kg ha^{-1} to 311kg ha^{-1} while available phosphorus varied from low to medium. Details of the physical-chemical soil properties are presented in Table 1.

Field Experimental Design

Experiments were arranged in a split plot design in both locations with four replications. The treatments included fivephosphorus fertilizer levels and three sorghum varieties. The fertilizer treatments were applied in the form of single super phosphate (SSP) where P-levels varied from 0 – 60kgha^{-1} at 15kg interval, 60kg of N and 30kg of K_2O applied at a constant rate per hectare using urea and muriate of potash respectively.P-application rates of 0, 15, 30, 45, and 60 kg ha^{-1} were applied as main plots while sorghum varieties: ICSV-400, CSR-01 and the control varietywere considered as subplots. The gross size of each plot was 15 m^2which consisted of four ridges,5m long spaced at 75 cm apart. Sowing was done at 30 cm between plants, gaving a total plant population of 44,444 hills ha^{-1}.

Field operations and Data collection

The field was disc-harrowed and ridged before planting. The first cropping season was sown on the 7th July at Minjibir and 19th July at BUK, in 2014, while in the second year they were sown on 4th July at Minjibirand 20th July at BUK in 2015. Sowing was done after the rainfall

Table 1: Physical and chemical properties of the top-soil (0-20cm depth) at the experimental sites

Parameters	BUK		Minjibir	
	2014	**2015**	**2014**	**2015**
Soil pH value (1:2.5 soils: water)	4.86	5.7	5.01	5.35
Soil organic carbon (%)	0.417	0.299	0.196	0.359
Total Nitrogen (kg/ha)	311.5	157.2	163.3	235.83
Available P (kg/ha)	4.456	9.219	9.013	3.352
Available K (kg/ha)	0.890	0.346	0.776	0.346
Particle size proportion (%)				
Sand	79.85	78.64	92.3	82.64
Clay	9.91	10.08	3.36	16.08
Silt	10.2	11.28	4.35	1.28
Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam

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). The first fertilizer doses (full doses of P, K and half dose of N were applied by drilling method at sowing, while the second dose was applied between 4 and 6 WAP depending on rains. Weeding was done manually to keep the field weed free. At both locations, chlorophyll content of leaves was measured at 3 and 6 WAP using a Soil-Plant Analyses Development (SPAD) -502 chlorophyll meter (Minolta Corp., Ramsey, NJ, USA) and was expressed in arbitrary absorbance or SPAD values. All chlorophyll meter readings were taken at three spot between the stalk and the tip of the leaf on 5 randomly seleted plants, Leaf Area Index (LAI) were also measured at 3 and 6 WAP with Accupar LP-80 portable canopy analyser, readings were taken by placing the Accupar under the plant's canopy. Days to 50% flowering and maturity was observed accordingly while plant height (in cm) was 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 determined by harvesting the two center rows of each plot (approximate area of 7.5 m^2). Both panicle and stover were sun-dried for 2-week 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 above ground drymatter (TDM) on a sun-dried weight basis multiply by 100%.

Crop water requirement and water use efficiency

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 (K_c) for sorghum Eq. (1) (Doorenbos and Kassam, 1979). The Penman-Monteith equation was used to calculate reference evapotranspiration (ET_0) Eq. (2); the variables of this equation were described in FAO Irrigation and Drainage Paper No.56 (Allen et al., 1998). The method is of quite good accuracy and is usually used for calculations of evapotranspiration from farmlands.

$$ET_c = K_c ET_0 \qquad (1)$$

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

where

ET_0-reference evapotranspiration [mm day^{-1}],
R_n- net radiation at the crop surface [MJ m^{-2} day^{-1}],
G- soil heat flux density [MJ m^{-2} day^{-1}],
T- air temperature at 2 m height [°C],
u_2: wind speed at 2 m height [m s^{-1}],
e_s- saturation vapour pressure [kPa],
e_a- actual vapour pressure [kPa],
e_s - e_a :saturation vapour pressure deficit [kPa],
D - slope vapour pressure curve [kPa °C^{-1}],
ɣ- psychrometric constant [kPa °C^{-1}].

K_c –crop coefficient for sorghum in this study was 0.71 as stated in FAO-56 manual (Allen et al., 1998). However, the 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, crop evapotranspiration (ET_c) obtained from Eq. 1 was used to calculate water use efficiency (WUE) in Eqs. 3 and 4. 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 yield at harvest maturity, using the following equations by Kuslu *et al.*, (2010) and cited by Hadebe et al., (2017).

$$\text{Biomass WUE} = B/ET_c \qquad (3)$$

$$\text{Grain yield WUE} = Y/ET_c \qquad (4)$$

Where B = Dry above ground biomass (kgha^{-1})

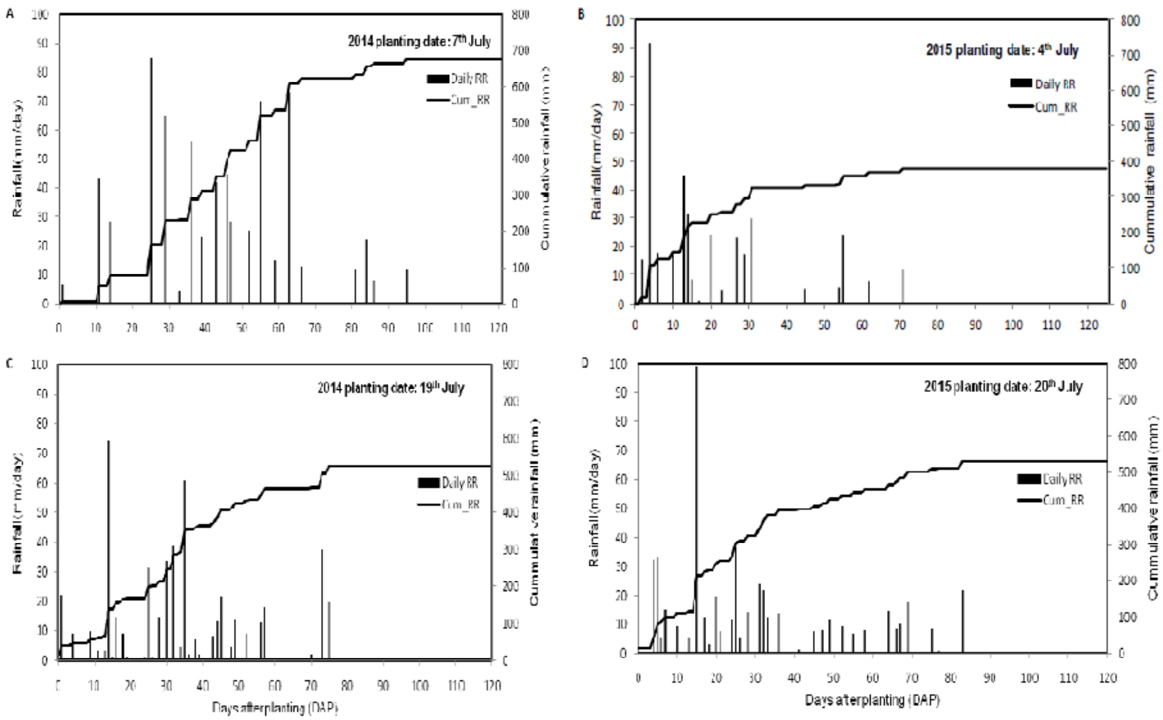

Figure 1: Daily and cumulative rainfall distribution from planting to maturity at Minjibir (A&B) and BUK(C&D)

ET_c = Crop/field evapotranspiration(mm)
Y = Grain yield ($kgha^{-1}$)

Agronomy Phosphorus Use Efficiency

The phosphorus use-efficiency, in terms of agronomic phosphorus useefficiency (APUE) was calculated as per the following formula (Prasad, 2009) and reported as kg grain/kg nutrient (NPK) applied.

$$\text{APUE} = \frac{Y_f - Y_c}{P_a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4)$$

Where; Y_f: Grain yield (kg/ha) in fertilized plot; Y_c: Grain yield (kg/ha) in control plot; P_a: Nutrient (N+ P_2O_5+ K_2O) applied (kg/ha).

Statistical Analysis

All the data were subjected to analysis of variance (ANOVA) using GENSTAT analytical tool (14th edition). P-fertilizer levels and cultivar was taken as treatment to determined level of significance. Fisher's least-significant difference (LSD) test were computed where the F values were significant at the P = 0.05 level of probability Gomez and Gomez, (1984). The data were also subjected to regression analysis to determine the relationships between grain yield and yield attributes as well as other plant traitsacross varieties considered at both locationsusing correlation coefficient (R) analysis.

RESULTS AND DISCUSSION

Effects of rainfall distribution on growth and yield development

Figure 1 shows the daily rainfall distribution and total amount from planting to physiological maturityin 2014 and 2015 growing seasons. In Minjibir (Figure 1A and B), the total rainfall received during 2014 and 2015 cropping seasons were 677 and 380 mm respectively. Most of the rain events indicated higher intensity with daily amount>30mm and it's occurred between 5 and 65 DAP, which accounted for 70% of annual total rainfall recorded in both seasons.However, the rainfall distribution was more favourablein 2014 than 2015 cropping seasonwhich was 43% higher and less dry spellduring vegetative/stem elongation while theflowering and grain filling stage coincided with the beginning of dry season. Figure 1C and D indicatedthat similaramount of total rainfall (526 and 533mm) were received in BUK during the two cropping

Table 2: Effect of P-fertilizer levels and varieties on leaf chlorophyll content, LAI and plant height in the two locations (mean of 2014 & 2015 cropping season)

Treatments	SPAD 3WAP	SPAD 6WAP	LAI 3WAP	LAI 6WAP	Plant height(cm)	SPAD 3WAP	SPAD 6WAP	LAI 3WAP	LAI 6WAP	Plant height (cm)
	←Minjibir				→	←BUK				→
Fertilizer (F)										
0	39.90	40.85	2.090	2.070	175.6	36.06	45.8	3.044	2.387	230.9
15	40.54	41.38	2.354	2.485	201.1	38.50	44.2	3.218	2.440	251.4
30	39.59	41.10	2.473	2.274	195.2	40.06	43.9	3.055	2.390	253.8
45	43.28	43.74	2.474	2.824	**216.5**	40.07	49.6	3.137	2.462	234.4
60	41.54	41.30	2.482	2.829	203.2	39.55	44.4	3.0478	2.487	**256.1**
P of F	**0.011**	**0.154**	**0.122**	**<.001**	**<.001**	**<.001**	**0.402**	**0.848**	**0.981**	**<.001**
LSD (0.05)	2.250	2.516	0.3444	0.3901	17.49	1.604	18.83	0.3652	0.3809	13.46
Variety (V)										
CSR01	41.57	41.65	2.682	2.662	217.9	39.79	45.8	3.339	2.788	273.0
ICSV400	39.88	41.73	2.136	2.173	137.6	38.20	42.6	2.755	1.917	168.3
Local	41.47	41.65	2.305	2.655	239.3	37.95	44.4	3.207	2.595	294.7
P of F	**0.101**	**0.996**	**<.001**	**0.002**	**<.001**	**0.008**	**0.257**	**<.001**	**<.001**	**<.001**
LSD(0.05)	1.743	1.949	0.2667	0.3022	13.54	1.242	14.58	0.2829	0.2950	10.43
CV	9.6	10.5	25.3	27.2	15.4	7.2	11.9	20.5	27.3	9.6

seasons, no significant dry spell occurred during the vegetative growth stage, however the long dry spell experience signalled the beginning of terminal drought which coincided with the flowering and grain filling period.As observed in both locations and cropping seasons, the rainfall distribution pattern slightly fell below water need for sorghum in Semi-Arid environment (Allen *et al.,* 1998) except for the 2014 cropping season in Minjibir, but the varieties used exhibited drought tolerant trait which agreed closely to previous studies on sorghum reported by ICRISAT, (2009). However, CSR01 producedthe lowest yields compared to other two varieties in both seasons, whichimplied that yield development couldbe greatly affected if moisture falls below crop water use especially when floweringoccurstoo lateinto the beginning of terminal drought. Similar results were reported by Kouressy et al., (2008) on the effects of sowing dates and photoperiodism of sorghum.

Effect of P-Fertilizer Applications and Variety on Sorghum Morphological Traits

Leaf chlorophyll concentration and Leaf area index

P fertilizer treatments at 3WAP significantly affected the leaf chlorophyll concentration(SPAD),in both locations while no significant difference was recorded at 6WAP (Table 2). Higher chlorophyll concentrationwere observed with high P-fertilizerlevel of 45 kg $P_2O_5ha^{-1}$compared to control treatment. No significantdifferences were recordedamong the varieties for SPAD values at 3 and 6 WAP in Minjibir, though significant differences were observed at 3 WAP in BUK.

P-fertilizer treatments did not have significant effect on LAI at 3 WAP in both location and at 6 WAPin BUK, but it significantly affected LAI at 6 WAP in Minjibir. Highly significant differences were, however observed among the varieties in both locations for LAI at 3 and 6 WAP. P-fertilizer treatments increased LAI by 10-36% in Minjibir compared to control treatment. In both locations, variety CSR01 recorded highest mean values at 3 and 6WAP with values of2.68 and 2.66m^2/m^2at Minjibirand 3.34 and 2.79m^2/m^2at BUKrespectively. Though these were not significantly differen from the local variety. The lowest values of 2.14 and 2.17 m^2/m^2 in Minjibir and 2.76 and 1.96 m^2/m^2 in BUK were recorded by ICSV400 .

Plant height

Significant differences were observed among the P fertilizertreatments for sorghum plant height though the differences were not linear (Table 2). At Minjibir, the plant height increased with increasing P up to 45 kg ha^{-1}, after which P increase lead to negative effect on height. The

Table 3: Correlation analysis of grain yield with growth parameters and yield components of sorghum in Minjibir and BUK across the varieties.

Character	Minjibir		BUK	
	R	P-value	R	P-value
SPAD(3WAS)	**0.26**	**0.033**	0.04	0.194
SPAD(6WAS)	0.12	0.725	0.09	0.133
LAI (6WAS)	**0.32**	**0.051**	0.03	0.712
LAI (9WAS)	-0.06	0.802	0.1	0.096
Plant height(cm)	**0.33**	**0.001**	0.11	0.135
1000-seed weight(g)	-0.07	0.471	**-0.26**	**0.001**
Stalk yield (kgha^{-1})	**0.18**	**0.053**	**-0.89**	**<.0001**
Harvest Index(%)	0.16	0.089	**0.55**	**<.0001**

**, * , ns means P-value is≤0.01, ≤0.05 and ≥ 0.05level

tallest plants(216.5cm) were recorded with the application of 45 kg Pha^{-1} and the shortest plants (175.6 cm) from thecontrol (0 kg Pha^{-1}).In BUK, the tallest plants (256.1cm)were recorded with the application of 60 kg Pha^{-1},while the shortest plants (230.9 cm) were recorded in the control treatment (0 kg P ha^{-1}).Similar results were also reported byBilal *et al.,* (2000); Roy and Khandaker (2010) that plant height increased progressively up to harvest over control with the application of N and P fertilizer. Among the varieties, the local cultivar was observed as the tallest plants witha mean value of 239 cm at Minjibir and 295 cm at BUK while shorter plants witha mean value of 138 and 168 cm were obtained from ICSV-400 in Minjibir and BUK respectively.

Relationship Between Grain Yield and Crop Growth Parameters

Table 3 displayed the correlation coefficients between growth parameters and yield components association with grain yield in both locations. SPAD at 3WAP, LAI at 6WAP, plant height and stalk yield were significantly and positively correlated (0.26*,0.32*,0.33** and 0.18* respectively) with grain yield at Minjibir. In contrast, only 1000-seed weight and stalk yield showed significant negative correction (-0.26** and -0.89**) with grain yield at BUK while harvest index(HI) showed significant positive correction of 0.55** with grain yield. This result is in close agreement with previous findings by Gul *et al.,* (2005) where grain yield was reported to have been strongly associated with total biomass and harvest index as well withmajor yield components. Thisimpliesthat grain yield is a function of a multiple of factors thatmay be regulated by different genetic mechanisms. Also, the significant positive correlation of SPAD at 3WAP and LAI at 6WAP with grain yield at Minjibir and non significant relationship in BUK suggeststhat early vigour positively contributes to grain yields specially in thelow soil fertility situations. Therefore agronomic practices that ensure vigorous and healthy seedlings should be encouraged as it will significantly contribute to yield increase.

Effects of P-Fertilizer Application Rate and Sorghum Variety on Yield and Yield Components

Thousand seeds weight, Grain and Stover yields, and Harvest Index

Table 4 shows the effect of P-fertilizer application and sorghum varieties on 1000-seed weight, grain and stover yieldand harvest index in the Sudan savanna of Nigeria. The result showed that year had a significant effect on allfour variables in both locations. While mean 1000 seed weight was significantly higher in 2014 than 2015, mean sorghum grain yield was significantly higher in 2015 than 2014 in both location.This was not only as a result of the weather condition (rainfall) but also effect of soil fertility (Table 1). ThoughP-fertilizer rates had no significant effect 1000 seed weight, significant differences were observed among the varieties in both locations. This implies that seed weight is more genectically influenced than environmental. This is line with the report of Ashraf *et al.* (1999)who noted that 1000-seed weightis an important yield determining component and reported to be a genetic trait that is influenced least by environmental factors. The local variety hadsignificantly higher mean seed weight of 32.8g at Minjibir and 30.3g at BUK compared to ICSV400which had 23gat Minjibir and 21gat BUK respectively.

Highly significant differences(P<0.01) were observedamong P-fertilizer treatments and among the sorghum varieties for grain yield in both locations. The

Table 4: Effect of P-fertilizer levels and variety on 1000-seed weight, grain yield, stover yield and harvest index in the two locations for 2014 and 2015 cropping seasons

Location	**Minjibir**				**BUK**			
Treatment	**1000-seed weight**	**Grain yield**	**Stover yield**	**Harvest Index**	**1000-seed weight**	**Grain yield**	**Stover yield**	**Harvest Index**
	(g)	**(kgha^{-1})**		**(%)**	**(g)**	**(kgha$^{-1)}$**		**(%)**
Year								
2014	30.35	2806	6188	32.53	30.36	2329	11167	19.5
2015	22.74	2903	7527	29.75	20.63	2925	6586	31.0
P of F	**<.001**	**0.009**	**0.002**	**0.006**	**<.001**	**<.001**	**<.001**	**<.001**
LSD (0.05)	1.187	71.7	811	1.94	1.71	116.6	561.1	1.3
Fertilizer (F)								
0	26.00	2297	5213	33.1	24.69	2109	8188	22.4
15	26.34	2753	6968	30.5	25.93	2499	9056	23.4
30	26.28	2974	7479	30.7	26.59	2702	9090	25.2
45	26.59	3156	6952	32.9	24.20	2929	9271	26.1
60	27.53	3093	7676	30.5	26.08	2896	8776	27.5
P of F	**0.546**	**<.001**	**0.085**	**0.607**	**0.365**	**<.001**	**0.585**	**0.038**
LSD(0.05)	1.88	128	1838	4.72	2.703	171.4	1522	3.3
Variety (V)								
CSR-01	24.01	2551	7509	26.8	25.48	2429.	9401	21.8
ICSV-400	22.87	2910	4885	38.0	20.70	2651	6319	30.3
Local	32.76	3102	8179	29.9	30.30	2800	10910	22.7
P of F	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**0.002**	**<.001**	**<.001**
Mean	26.55	2994	7269	31.1	25.50	2756	8876	26.0
LSD(0.05)	1.453	119	984	2.47	2.094	198.6	767	2.2
CV (%)	12.3	6.8	16.4	16.8	18.3	12.1	17.0	14.2
Interaction								
Y* F	ns	*	ns	ns	Ns	*	ns	ns
Y* V	ns	**	**	**	Ns	ns	**	**
F*V	ns	*	ns	ns	Ns	ns	ns	ns
Y*F*V	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; ****, *** mean significant different at 0.01, 0.05level of probability; **ns**-not significant

grain yield was significantly higher in 2015 than 2014 in both locations. In both locations the grain yieldsincreased with increase inP fertilizer rates from zero to 45 kg ha^{-1},beyond which the yielddropped. The result showed yield increased by 20-37% at Minjibir and 19-39% at BUK over control treatment.The highest mean yield (3156 kg ha^{-1} at Minjibir and 2929 kg ha^{-1} at BUK) was obtained with 45kg P_20_5 ha^{-1} rate, which was significantly different from P rates at 0, 15and 30 kgP_20_5 ha^{-1}. These results showed that P-fertilization could increase sorghumgrain yields, but excessive P fertilization had negative effect. This is similar to the results obtained by Ayub, et al., 1999, who noted a progressive grain yield increase in sorghum with P fertililizer application up to 50 kg P_20_5+ 100 kg Nha^{-1}.Though most researchers focused on N fertilizer application ratethan P for for cereals including sorghum, however research by Buah *et al.* (2012), demonstrated a parabolic relationship betweenP fertilization and sorghum grain yield in theGuinea savanna zone, which implies that when P rate surpassed a certain threshold,the grain yields greatly declined.

However if the residual soil P is high the response is less. This was the observation of Sahrawat et al 1995, who recorded sorghum grain yield increased from 0.14 t (no P added) to 3.48 tha^{-1} with P added at the rate of 40 kg P ha^{-1},in the first year of the experiment,58% less effective in second year as a result of residual effect. In a similar experiment, Bayu *et al.,* 2002, found that responses of sorghum to P fertilization were variable between seasons and locations due possibly to the high initial soil P.Local cultivar had significantly higher mean grain yields(P < 0.01) in both locations (3102kg ha^{-1} and 2800kg ha^{-1} in Minjibir and BUK respectively) than ICSV400 (2910kg ha^{-1} at Minjibir and 2651kg ha^{-1} in BUK),while the lowestmean yield was obtained from CSR-01 at both sites.This was due to the different morphological characteristics of these varieties.The local variety recorded higher yield because it has higher drought tolerance than CSR01 despite being of similar maturity.While major indicators (plant height, LAI and SPAD) suggest that BUK is of higher soil fertility, the grain yields in Minjibir were higher than in BUK especially in 2014, this was because the rain stopped 95 DAP in

Table 5a: Interaction of P-fertilizer and varietyon sorghum grain yield Minjibir

Treatment	2014				2015			
	CSR01	**ICSV400**	**Local**	**Mean**	**CSR01**	**ICSV400**	**Local**	**Mean**
0	1842	2097	2756	2232	2089	2418	2580	2362
15	2343	2568	3110	2674	2465	2981	3052	2833
30	2466	2980	3234	2893	2613	3185	3364	3054
45	2685	3078	3402	3055	3037	3377	3359	3258
60	3114	3213	3203	3177	2860	3207	2964	3010
Mean	2490	2787	3141	2806	2613	3034	3064	2903
Grand mean	**2855**							
LSD(Y*F)	165.1							
LSD(Y*V)	145.3							
LSD(F*V)	244.9							
LSD(Y*F*V)	309.5							

Table 5b: Interaction of P-fertilizer and variety

Treatment	CSR01	ICSV400	Local
0	1966	2258	2668
15	2404	2775	3081
30	2540	3083	3299
45	2861	3228	3381
60	2987	3210	3084
Mean	2551	2910	3102
LSD(F*V)	244.9		

minjir compared to 70 DAP in BUK (Fig 1). Theses results suggest that medium maturing sorghum varieties should be planted at the latest, in the first 7 day of July in both locations.A planting date trial and and simulation model is recomended to validate this results inview of climate variability experienced in the zone.

Table 5a shows theinteraction effectsof year, fertilizer and variety on sorghum grain yield at Minjibir.There were significant year xfertilizer interactions as well as year xvariety and fertilizer xvariety interactions for sorghum grain yields in Minjibir. In 2015 mean sorghum grain yields obtained at the lower P fertilizer rates (0 to 45 kg P_20_5 ha^{-1}) were significantly higher than mean sorghum grain yieds obtained in 2014, while mean sorghum grain yields obtained at the higher P fertilizer rates (60 kg P_20_5 ha^{-1}) was significantly lower than mean soghum grain yield obtained in 2014. In 2014,local sorghum varietiy (3141 kg ha^{-1}) produced significantly higher mean grain yields than other varieties while there were no significant differences between mean grain yield produced by local variety (3064 kg ha^{-1}) and ICSV400 (3034 kg ha^{-1})in 2015. At low P levels (0 to 30 kg P_20_5 ha^{-1}), local sorghum variety produced significantly higher mean grain yields than the other varieties(Table 5b), however at 45 kg P_20_5 ha^{-1}there was no significant difference between mean grain yield of the local variety (3381 kg ha^{-1}) and ICSV400(3228 kg ha^{-1}) though both produced significantly higher mean grain yields than CSR01 (2861 kg ha^{-1}). At 60 kg P_20_5 ha^{-1} ICSV400 (3210 kg ha^{-1}) produced higher mean grain yield than local sorghum variety (3084 kg ha^{-1}). ICSV-400, an early maturing medium height variety was more sensitive to fertility status and produced higher grains in the higher P fertilizer rates.This may also be responsible for the higher mean grain yield obtained from ICSV-400 in 2015.

Stover yield is a function of photosynthetic rate and the proportion of the assimilatory surface area. P-fertilizer treatments did not significantly affect stover yield in both locations (Table 4). However, highly significant differences existed among the varieties with local cultivar producing the highest mean stover yields (8179 kg ha^{-1}at Minjibir and 10910 kgha^{-1} at BUK), while ICSV-400 produced lowest mean yield of 4885kg ha^{-1} and 6319kg ha^{-1} at Minjibir and BUK respectively.The physiological efficiency of assimilates from source into economic sinks is known as harvest index (HI). As shown in Table 4, the effect of P-fertilizer level on HI indicate no significant differences at Minjibir but significant difference was observed at BUK, while the sorghum varieties differed significantly in both locations. In BUK where P fertilizer treatments significantly affect HI, the HI increase with increase P levels in

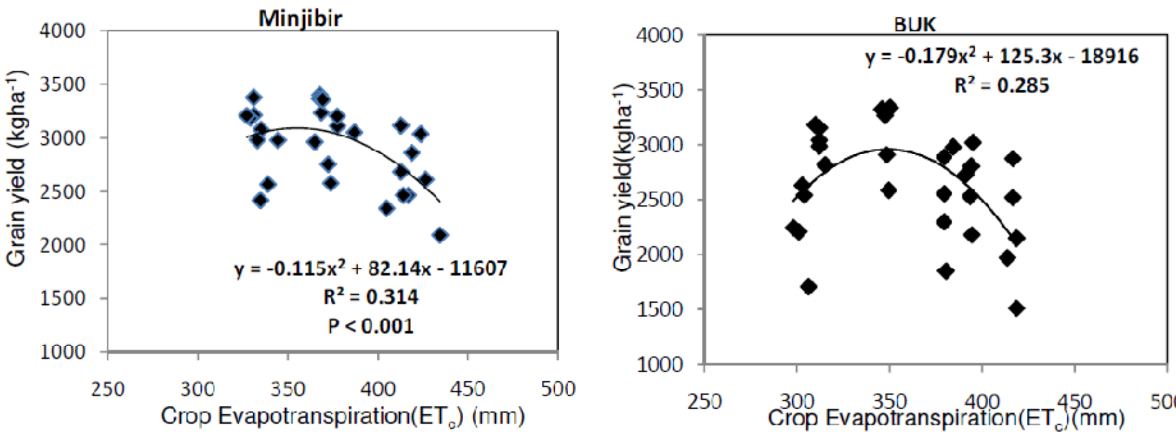

Figure 2: Quadratic relationship between crop evapotranspiration (ET_c) and grain yield of sorghum in Sudan Savanna zone, Nigeria.

agreement with the report of Lawrence *et al.* (2008) on maize. However in Minjibir where there were no significant difference among the P levels for HI, there was also no linear effect of the fertilizer application.Among the varieties, ICSV-400 had higher HI (38% and 30.3%) than other varieties while CSR-01 showed the lowest HI (26.8% and 21.8%) indicating genotypic variations in partitioning efficiency. However this was because ICSV 400 produced less stover than the other varieties.

The relationship between grain yields and seasonal ET_c was bestdescribed by a quadratic function obtained by regression analysis (Fig. 2). The results indicate highly significant differences ($P<0.001$), the coefficient of determination (R^2) implies that 31.4 % of yield at Minjibir and 28.5% of yield at BUK could be directly explained by estimated seasonal crop evapotranspiration (ET_c) across the varieties. In the present study,the result further showed that grain yield did not increasewhen seasonal ET exceeded a certain critical value, e.g. 423 mm at Minjibir and 416mm at BUK.This could be associated to below-average rainfall received in 2015 experimentresulting to sub-optimal water utilization due to delayed planting.Though,the crop water requirementfor sorghum range from 450 to 650mm in a season(Bodner, *et al.,*2007),the accessibilityis determined by soil water storage and total rainfall received. Our result may indicatethat the higher crop yield in this area will rely more on rainfall and soil water storage in order to maximize the micro-nutrient (P) in the soil.

Crop evapotranspirationand water use efficiency

In semi-arid farming system, crop water use estimated by seasonal $ET_c$is supplied majorly from rainfall during the growing season and partly from the soil-water storage before planting. The effects of P fertilizer rates on ET_c, WUE (for grain and biomass) and agronomy phosphorus use efficiency (APUE) are presented in Table 6. The result revealed that the $ET_c$was significantly influenced by different P-fertilizerrates at Minjibir, but nosignificant difference was observed at BUK. Also, ET_c decreased slightly between 0 kg ha^{-1} and 60 kg P_20_5ha^{-1}. The estimated ET_c was sub-optimal among P fertilizer treatments in both locations compared to required water use for sorghum crop as reported by FAO-56; this could be associated withcessation of rainfallprior to grain filling. The lower crop water use estimated by ET_calso confirming water stress experienced by the crop at a certain growth stages,particularly the late maturing varieties (CSR-01 and local) due to delay planting. Among the varieties, CSR-01 indicated highest values of 421mm and 405mm at Minjibir and BUK respectively, while the lowest mean values were obtained from ICSV-400 (330 mm and 307 mm) at both locations respectively.

Highly significant differences existed between P-fertilizer rates and varieties for grain yield WUE, but no significant difference between P rates for biomass WUE.However, as P rates increased, the WUE for grain yield and biomass increased, beyond 45 kgP_20_5ha^{-1}, no further increase was observed for grain WUE, which indicated that P application in excess of 45 kg ha^{-1} had no favourable effect for water utilization. A similar result was obtained by Zhou *et al.* (2011) on response of fertilizer application rates on WUE in a winter wheat–summer maize cropping system. The optimal grain WUE (8.6 and 8.3 kg ha^{-1}mm^{-1} in Minjibir and BUK respectively) was recordedat 45kgP_20_5ha^{-1}.A study by Parmar and Sharma (1996) alsofound that WUE increased with a higher amount of P fertilizer under mulch conditions for sorghum. Additionally, the significant differences among the varieties are likely due to different physiological maturation period. Among the varieties, ICSV-400 had mean highest valuesof 9.3kg ha^{-1}mm^{-1} and 8.6kg ha^{-1}mm^{-1} at Minjibir and BUK respectively, and the results were at par for grain WUE while local recorded the mean highest

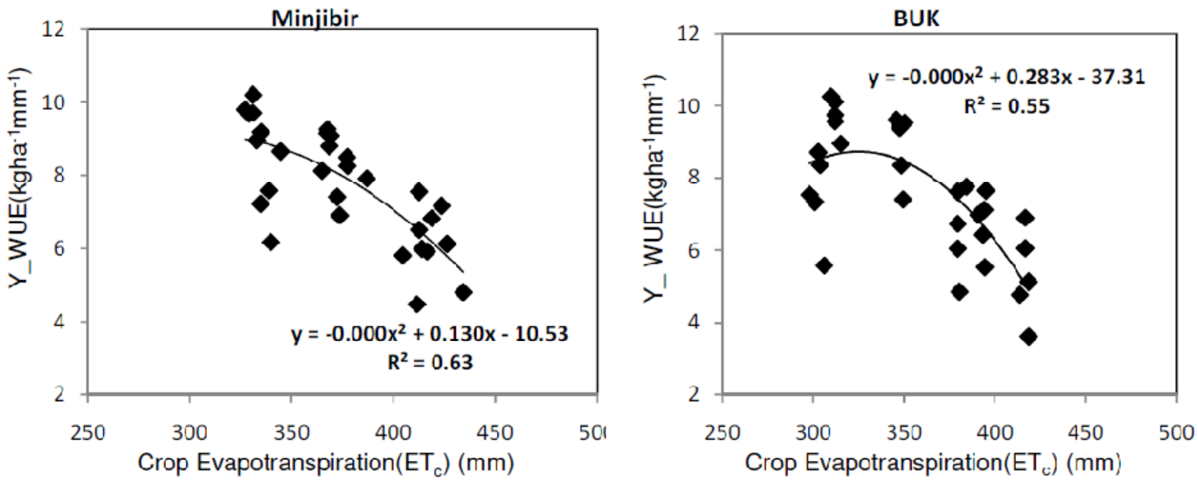

Figure 3: Quadratic relationship between crop evapotranspiration (ET_c) and grain WUE of sorghum in Sudan Savanna zone, Nigeria.

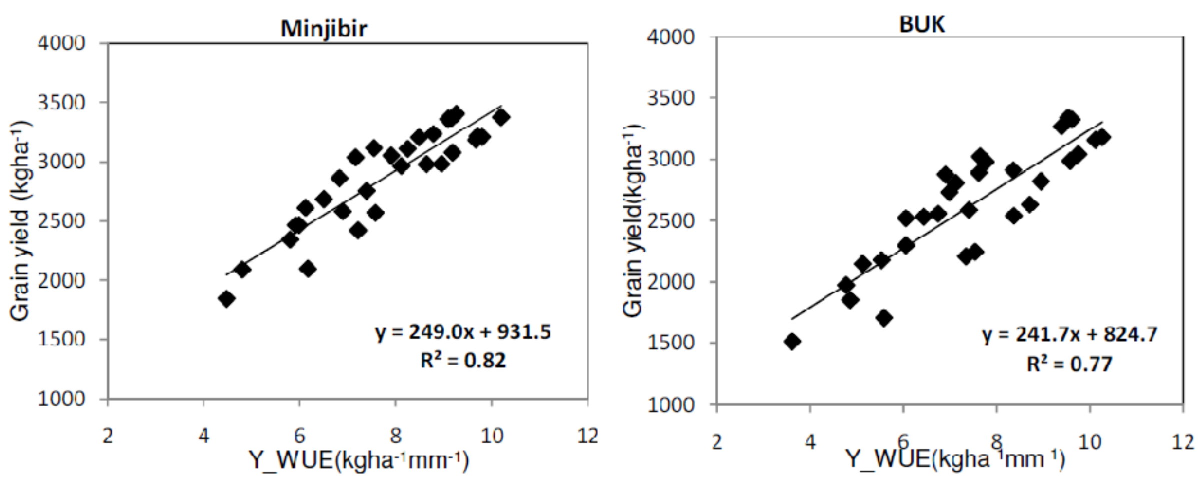

Figure 4: Linear relationship between grain_WUE and grain yield of sorghum in Sudan Savanna zone, Nigeria.

value (32.6kg ha^{-1}mm^{-1} and 37.1kg ha^{-1}mm^{-1}) for biomass WUE inboth locations respectively. These results were in agreement to studyconducted by Li *et al.* (2001) during a dry year on the semi-arid Loess Plateau of the Northern China Plain, where the influence of water and P on yield and WUE of spring wheat was examined. Regression analysis produced a quadratic relationship betweenET_c and Y_WUE (Fig. 3) which shows that 63 % at Minjibir and 55% at BUK grain WUE variations could be directly explained from ET_cacross the varieties. Also, the grain yield increased linearly with WUE at both locations indicate strong correlations positive correlations (R = 0.91 and 0.87) between WUE and grain yields (Fig. 4). The maximum grain WUE did not correspond to the maximum grain yield in this study which indicates that the crop can gain a higher yield using lesser water, especially if the sorghum flowered prior to terminal rainfall. On the contrary, biomass and grain yield WUE for the local variety among P rates generally improved with low rainfall. This reinforcesour findings in this study that local cultivar (mostly landrace) is highly suitable for production under severe water stress, as more ‘food per drop’ can be produced with less rainfall.

Agronomy phosphorus use efficiency

Agronomy phosphorus use efficiency (APUE) was significant among P-fertilizer level and varieties at both sites (Table 6). At both locations, APUE was highest value with P rates of 15kgha^{-1} and withincrease in P rate it decreased. Sorghum genotypes differed significantly, ICSV-400 exhibitedmaximum APUE (24.8) in Minjibir while CSR-01 and local were at par (21.2) in BUK.Though dryland is limited in available phosphorus, the results showed it required small quantity of P-fertilizer to achieve optimum yield.

Table 6: Effect of P-fertilizer levels and variety on crop evapotransipiration (ET_c), yield water use efficiency(Y_WUE), biomass water use efficiency (B_WUE) and agronomy phosphorus use efficiency (APUE) in the two locations for 2014 and 2015 cropping seasons

Location	**Minjibir**				**BUK**			
Treatment	**ET_c**	**Y_WUE**	**B_WUE**	**APUE**	**ET_c**	**Y_WUE**	**B_WUE**	**APUE**
	mm	**$kgha^{-1}mm^{-1}$**			**mm**	**$kgha^{-1}mm^{-1}$**		
Year								
2014	374	7.97	25.3	21.4	367	6.5	36.5	23.9
2015	374	8.25	29.5	21.3	351	8.4	27.2	14.7
P of F	**0.86**	**0.013**	**<.001**	**0.903**	**<.001**	**<.001**	**<.001**	**<.001**
LSD (0.05)	4.68	0.22	2.28	2.15	1.5	0.34	1.75	
Fertilizer (F)								
0	374	6.16	20.0	-	361	6.0	28.4	-
15	376	7.41	25.7	30.40	358	7.2	32.3	26.0
30	375	8.05	27.9	22.55	359	7.7	32.6	19.8
45	373	8.57	27.1	19.09	359	8.3	33.8	18.2
60	372	8.42	29.0	13.27	359	8.2	32.2	13.1
P of F	**0.077**	**<.001**	**0.597**	**<.001**	**0.409**	**<.001**	**0.139**	**0.005**
LSD (0.05)	3.28	0.37	5.37	4.54	3.4	0.47	4.30	5.77
Variety (V)								
CSR-01	421	6.32	25.8	21.3	405	6.0	30.9	21.4
ICSV-400	330	9.33	23.9	24.8	307	8.6	29.2	15.0
Local	372	8.69	32.6	17.8	365	7.7	37.1	21.4
P of F	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Grand Mean	375	7.7	27.4	21.3	359	7.8	31.9	19.3
LSD (0.05)	4.34	0.30	2.70	2.53	1.8	0.57	2.25	3.48
CV (%)	9.5	7.3	22.5	27.2	1.4	12.5	15.0	27.7
Interaction								
Y* F	ns	*	ns	ns	ns	*	ns	ns
Y* V	*	**	*	**	**	ns	**	ns
F*V	*	**	ns	ns	ns	ns	ns	ns
Y*F*V	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; *,** * mean significant different at 0.01, 0.05level of probability; **ns**-not significant*

CONCLUSION

The study had demonstratedthe application of P fertilizer applicationshad influenced grain yields, thousand-seed weights, harvest index, ET_c, WUE and APUE of the three physiologicallydifferent sorghum varieties (CSR-01, ICSV-400 and local)in the Sudansavanna agro-ecological zone of Nigeria.Increased P-application rates significantly increased grain compared to the control. SPAD at 3 WAP significantly correlated with grain yields, indicating that agronomic activities that ensured high seedling vigor and health should be encouraged for high grain yields.However, optimum grain yield among P rates was obtained at 45 kg P_2O_5 ha^{-1}at both sites. There was a significant difference among the P-fertilizer rates and varieties for the ET_c, grain WUE and APUE,but no significant difference was observed for biomass WUEat both locations. With increased P-fertilizer rates, ET_cdecreased slightly by 0.5 -1.5% over control treatment (without P-fertilizer) and P-fertilizer rates increased grain WUE by 20-38% at both locations, while biomass WUE increased by 29-45% at Minjibir and 13-19% at BUK.Also, APUE decreased with increased P rates and 15kg$P_2O_5$$ha^{-1}$ indicated the highest mean value which can be deduced as the optimal P efficiency rate. Though the varieties differed in the growing cycle, they all responded to P-fertilizer applications though at different rate.Localvarietyproduced the highest grain yield and Stover than CSR-01 and ICSV-400 indicating that the local variety could be valuable germplasm resources for production and potential crop improvement in a low rainfall area.Results suggest that medium maturing sorghum varieties should be planted at the latest, in the first 7 day of July in both locations. A planting date trial and and simulation model is recomended to validate this results inview of climate variability experienced in the zone. A comprehensive consideration of grain yieldand grain WUE of sorghum indicated significantly strong positive correlations. This could be an important method to obtain a balance between higheryields and lower water supplies of the semi - arid region by increasing its WUE.The soil N and P of the study areasare low, but the analysis showed that it falls within the range of available soil nutrient in the zone, hence, an application rate of 45kg P_20_5 ha^{-1} is therefore recommended as optimum for the Sudan savanna zone. Owing to the spatial variability in soil nutrients in the study area, site-specific fertilizer testing is needed to increase nutrient use efficiency and sorghum productivity.

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