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DROUGHT STRESS

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CO_2 exchange, dry matter accumulation and growth response of sorghum (*Sorghum bicolor* L. Moench) to terminal drought as affected by potassium and blended-NPSBZn fertilization

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Abstract

Sorghum production is constrained by terminal drought stress in semi-arid areas of north-eastern Ethiopia. Data from field experiments conducted in the region for two consecutive years (2015 – 2016) were used to investigate the effect of potassium (K) and NPSBZn-blended fertilizer (BF) inputs on the drought response of sorghum through analysis of gas exchange, dry matter accumulation and growth parameters. Leaf gas exchange properties varied strongly with K and BF application both under normal rainfall and drought conditions. Data taken at anthesis in drought-exposed sorghum indicated reduction of net photosynthetic rate (A_N) with BF supply. A_N declined from 15.7 μmol $CO_2/m^2/s$ in the control to 13.4 μmol $CO_2/m^2/s$ with application of 164 kg/ha BF. However, higher total dry matter yield was recorded at maturity in response to blended fertilizer and K inputs. Increasing supply of NPSBZn-blended fertilizer was associated with declining leaf K content, increasing intercellular CO_2 concentration and water use efficiency (WUE) during anthesis. Significant variations in crop growth rates were also observed in response to K and BF inputs. At physiological maturity, net assimilation rate (NAR) increased with K and BF inputs both under drought and normal rainfall conditions. In general, K application modulated the response of sorghum to BF input under both normal rainfall and drought conditions. Therefore, grain sorghum could benefit from early supply of K and BF fertilizer in drought prone areas of Northeastern Ethiopia.

KEYWORDS

blended fertilizer, chlorophyll, drought, gas exchange, growth, sorghum

1 | INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is the fifth leading cereal crop in the world after wheat, maize, rice and barley (Balole & Legwaila, 2006). It is the staple food of poor and the most food-insecure people, living mainly in the semi-arid tropics (Ali et al., 2009; Bibi et al., 2010). It performs better under adverse soil and weather conditions as compared to other crops (Ejeta & Knoll, 2007). However, significant reduction in the productivity of sorghum can occur in semi-arid conditions because of shortage and poor distribution of rainfall, soil fertility degradation and high temperatures (Doggett, 1988; Nguyen et al., 1997; Rosenow et al., 1997; Traore & Maranville, 1999).

Sorghum, a very important cereal crop in north-eastern Ethiopia, is widely adapted to the prevailing environmental conditions of the region, but its productivity is generally very low and variable due in part to poor soil fertility (Bayu et al., 2002). Despite being a drought tolerant crop, sorghum in arid and semi-arid regions is still affected by drought especially at terminal growth stages (Prasad et al., 2008), which causes significant yield reduction. Severe drought causes considerable yield loss in sorghum; flowering and grain filling are however more strongly affected compared to vegetative stage (Maiti & Satya, 2014).

The amount and pattern of rainfall have changed in many regions as a result of global climate change, the main factor triggering drought stress worldwide (Mishra & Singh, 2011; Rana et al., 2013), has led to increases in temperature and atmospheric CO_2 levels (Mishra & Singh, 2011; Nezhadahmadi et al., 2013). The changes are expected to be worse in regions such as Africa where the lack of economic development and poor institutional capacity could severely hinder coping mechanisms and increase vulnerability to the impacts of climate change (IPCC, 2001).

Low soil fertility in most arid and semi-arid regions, where sorghum is a major cereal crop is often related to low soil organic matter levels (Lal, 2004). Loss of soil organic matter is often accompanied by depletion of plant nutrients including potentially mineralizable N, P and S; increased soil bulk density; decreased water-holding capacity and hydraulic conductivity; decreased cation-exchange capacity; and ultimately reduced crop growth, yield and quality (Lal, 2004; Whitbread et al., 1998).

Most soils in north-eastern Ethiopia are reportedly low in organic matter and deficient in mineral nutrients (Bayu et al., 2006), hence necessitating mineral fertilization for improved crop productivity in the region. The problem is further complicated under drought where low soil moisture strongly affects availability and uptake of nutrients causing poor growth and low yields.

Limited water availability under drought generally results in limited total nutrient uptake and diminished tissue concentrations, severely affecting the acquisition and transport of nutrients to shoots (Farooq et al., 2009). On the other hand, positive crop response to improved soil fertility under arid and semi-arid conditions have been reported (Garg et al., 2004). Soil fertility-related stresses such as low levels of soil phosphorus and nitrogen exacerbate the effects of drought stress (Amede et al., 2004). Improved mineral nutrient status of plants is therefore considered crucial in increasing plant resistance to drought stress (Marschner, 1995).

Mineral nutrition generally affects the drought response of crops, including all physiological and biochemical processes (Cakmak, 2002; Marschner, 2012; Mengel et al., 2001). Nutrients such as P, K, Mg and Zn improve root growth which in turn increases the intake of water which helps in stomatal regulation and enhances drought tolerance (Mengel et al., 2001; Waraich et al., 2011). These nutrients also help maintain high tissue water potential under drought condition and improve drought tolerance by osmotic adjustment (Cakmak & Engels, 1999).

Fertilizer application commonly leads to improved grain and biomass yield of crops. However, in arid and semi-arid conditions, the higher biomass attained during early growth may lead to increased loss of the available soil moisture exposing the crop to drought stress at terminal growth stages where soil moisture is already limited mainly due to early cessation of seasonal rainfall. It is also equally important to determine the type and amount of nutrients added to balance the rate of growth and yield with the available moisture without sacrificing much of the final yield when the crop is exposed to drought at terminal growth stage. It is therefore essential to examine whether the response of sorghum to drought could be affected by K and BF, and whether the effect of BF could be influenced by the supply of potassium.

2 | MATERIALS AND METHODS

2.1 | Description of the study area

The experiment was conducted for two years (2015 – 2016) at a field research site of Sirinka Agricultural Research Center, near the town of *Haik* located 440 km Northeast of Addis Ababa, Ethiopia. The site is located geographically at 11°36′ N latitude, 39°64′ E longitude and at an elevation of 1,690 m above sea level (m.a.s.l) (Figure 1).

The soils of the experimental site are low in nitrogen, organic matter and phosphorus (Table 1). The study area lies in a region that is generally prone to recurrent drought and has experienced among the worst drought-related disasters recorded in the country's history.

2.2 | Climate of the area

Mean monthly temperature and total rainfall during the growing period (July through November) and the long-term (20 years) data are summarized and presented below (Figures 2 and 3). The amount and pattern of rainfall distribution during the growing season follows similar pattern to that of the long-term average.

2.3 | Methodology

Two experiments were conducted per season to compare response of sorghum to mineral nutrition under normal and drought conditions. The experiments were carried out for two years (2015 – 2016). The first experiment was planted at the normal planting date of the area, and the second experiment was planted 15 days later to expose the plants to terminal drought. The experiments were laid out as randomized complete block design (RCBD) with three replications. The size of each experimental plot was 5 m long and 4 m wide, with a total of six rows.

Sorghum seeds were hand drilled in a row spacing of 75 cm (between rows) by 1 5cm (within rows) and thinned after crop establishment to maintain a plant population of approximately 88, 888, which is recommended for the area (Bayu et al., 2002). The internal rows, leaving aside the outer two rows, were used for data collection.

The data were subjected to analysis of variance using MINITAB 19 (Minitab LLC, 2019). Significant differences between treatment means were compared and separated using the least significant

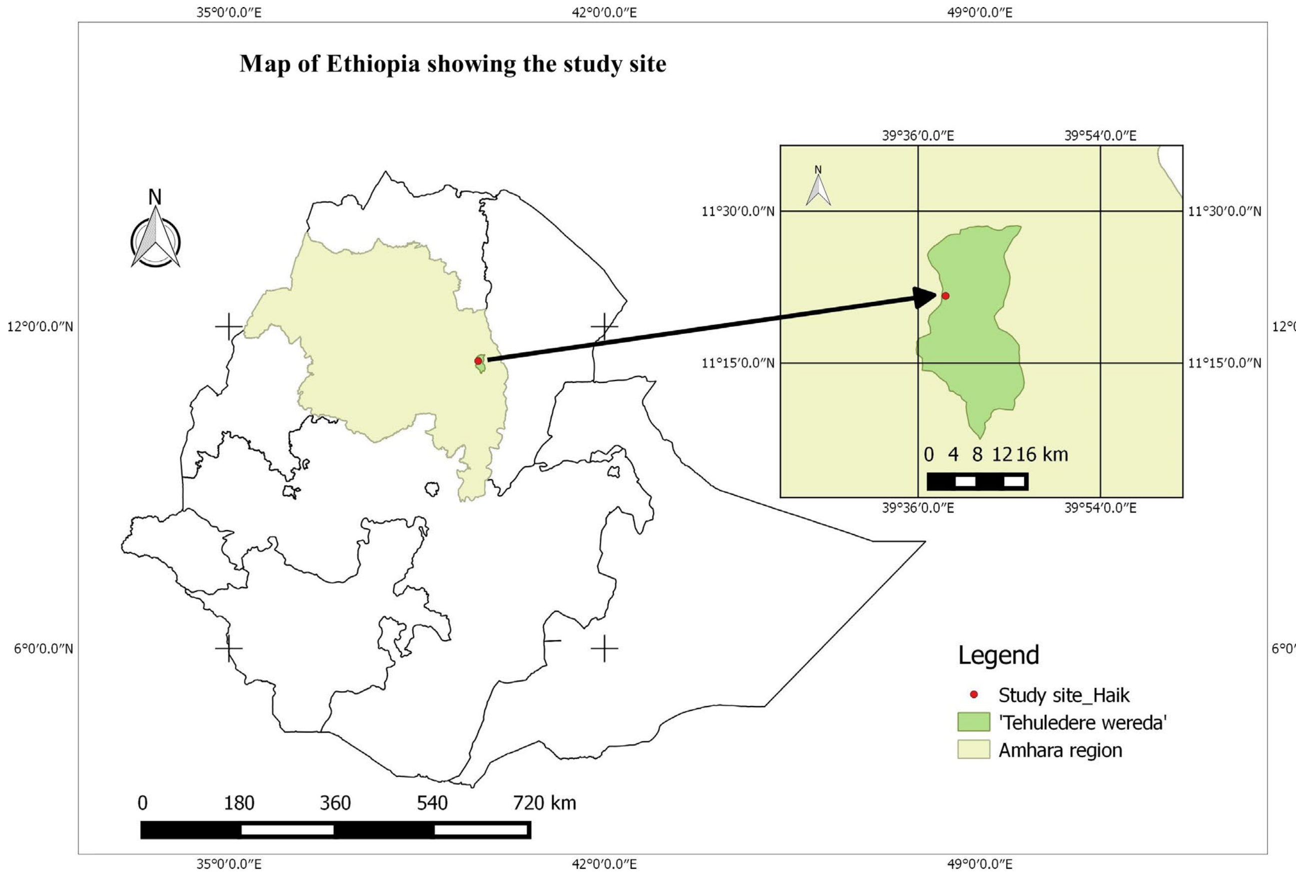


FIGURE 1 Map of Ethiopia showing the study site [Colour figure can be viewed at wileyonlinelibrary.com]

difference (LSD) test at the 0.05 and 0.01 probability levels (Gomez & Gomez, 1984).

2.4 | Treatment description

2.4.1 | Potassium (K)

Five levels of potassium (0, 20, 40, 60 and 80 kg/ha K_2O) were set with potassium chloride (KCl) as the source of K.

2.4.2 | Blended fertilizer (BF)

The term 'blended fertilizer' used in this study is in reference to **N, P, S, Zn** and **B** contained in a dry blended fertilizer prepared from commercially available fertilizers or nutrient sources, *viz.* **NPS** (*19% N-38% P_2O_5-7% S*), **$ZnSO_4$** (*36% Zn, 14% S*), **Borax** (*11% B*) and **Urea** (*46% N*).

The amount of each fertilizer required to fulfil the full dose of the recommended rates, that is 92 kg N/ha, 69 kg P_2O_5 ha^{-1}, 14.5 kg S/ha, 4.5 kg Zn ha^{-1} and 1 B kg/ha, was prepared by mixing 182 kg NPS (34.58 kg N, 69 kg P_2O_5, 12.75 kg S), 125 kg Urea (57.42 kg N), 12.5 kg $ZnSO_4$ (4.5 kg Zn and 1.75 kg S) and 9 kg Borax (1 kg B) resulting in 328.5 kg blended fertilizer (BF). Nitrogen was applied in two splits, one at sowing and the other side dressed at knee-height stage of the crop. Finally, BF was set at three levels as 0 (no fertilizer), 50% of the full dose (164 kg BF ha^{-1}) and 100% of the full dose (328.5 kg BF ha^{-1}).

2.4.3 | Treatment application and sowing

Factorial combination of the five levels of K and three levels of BF were investigated in two sets. The first set was tested on sorghum grown under normal rainfall condition, while the second was on sorghum exposed to terminal stage drought stress. Sorghum variety 'Teshale' was used in both years.

2.5 | Data collected

2.5.1 | Gas exchange

Fully expanded leaves were placed into LiCor extended reach chamber and allowed to equilibrate for 10 min before gas exchange was measured. Measurement was taken in the time interval from 10:00 to 12:00a.m. in three tagged plants from each plot. Net photosynthetic rate (A_N), transpiration rate (E), carbon dioxide concentration within the intercellular space (Ci) and stomatal conductance (G_s)

TABLE 1 Physicochemical properties of the soils used for the study

Parameters	Years 2015	2016
Soil pH	7.13	7.11
Total *N* (%)	0.17	0.16
Organic Carbon (%)	1.02	1.07
Organic matter (%)	1.75	1.84
Available P (Olsen), ppm	8.43	8.31
Cation-exchange capacity (CEC) (meq/100g soil)	32.04	37.13
Exchangeable bases:		
Ca^{2+} (cmol(+)/kg)	28.22 meq/100g	25.32
Mg^{2+} (cmol(+)/kg)	2.58	2.35
K^{+} (cmol(+)/kg)	2.25 meq/100g	2.41
Na^{+} (cmol(+)/kg)	4.17 meq/100g	3.43
Soil physical property		
Clay	33	35
Silt	38	37
Sand	29	26
Texture	Clay loam	

were determined using portable infrared gas analyzer (IRGA), LiCor 6,400 (Lincoln, Nebraska, USA). Water use efficiency (WUE) was calculated as net CO_2 assimilation (A) divided by transpiration (E) (Morison et al., 2008).

2.5.2 | Leaf chlorophyll content (SPAD readings)

Data on relative chlorophyll content of the leaves were collected using SPAD readings taken between 10.00 and 12.00 hr of the day. A 'Minolta Chlorophyll meter' model SPAD 502 (Japan) was used to take readings on five previously tagged plants from each plot. SPAD readings were therefore averages of three leaves per plant and five plants per plot.

2.5.3 | Growth Analysis and dry matter accumulation

Five randomly selected and tagged plants were used for all measurements of growth analysis. Growth records were taken three times during the cropping period at three-week interval starting from 42 days after emergence (DAE). Hence, sampling was done at 48, 69 and 90 DAE. Aboveground shoot dry matter was determined from

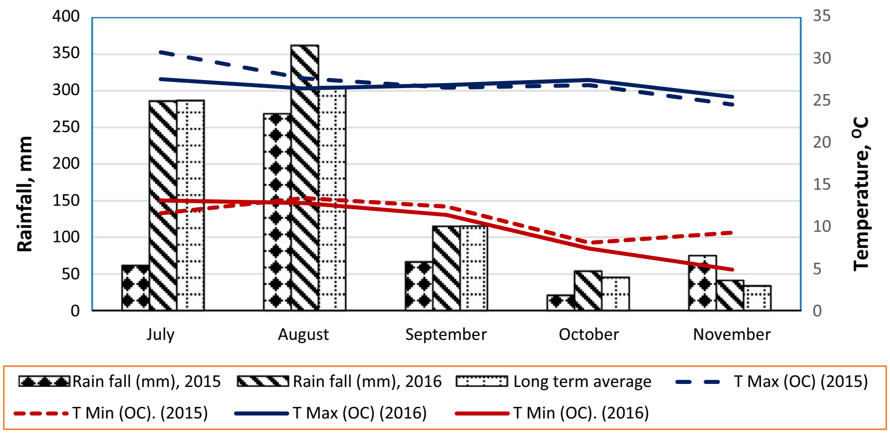


FIGURE 2 Rainfall (mm) and temperature (°C) during the growing period [Colour figure can be viewed at wileyonlinelibrary.com]

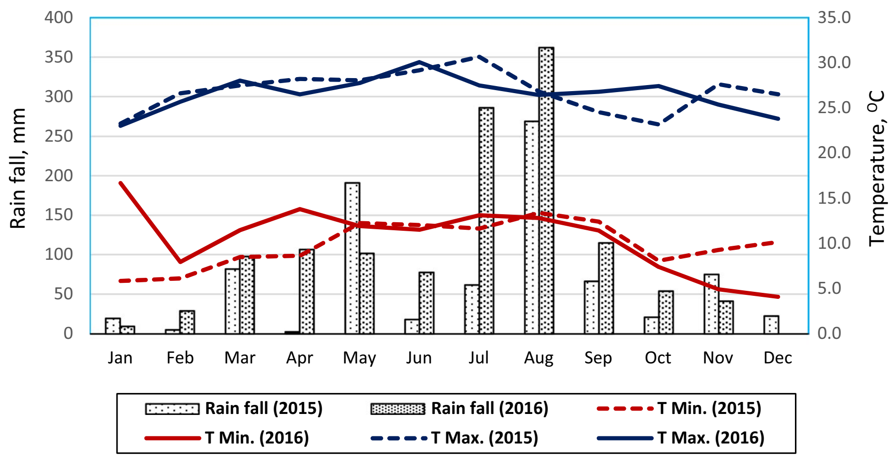


FIGURE 3 Rainfall (mm) and temperature (°C) in 2015 and 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

the harvested plants. The plants were sun dried, separated in to leaf, stem and panicle, and then oven dried at 70°C to constant weight. Shoot dry matter was then recorded as grams per plant.

Growth analysis was performed following Hunt (1990) on the basis of dry weight and leaf area measured at 48, 69 and 90 days after emergence (DAE). Crop growth rate (CGR), relative growth rate (RGR), net assimilation rate (NAR) and leaf area ratio (LAR) were calculated according to the following formulae:

$$CGR = \frac{w2 - w1}{t2 - t1} \tag{1}$$

$$RGR = \frac{\ln w2 - \ln w1}{t2 - t1} \tag{2}$$

$$NAR = \frac{w2 - w1}{t2 - t1} \times \frac{\ln L2 - \ln L1}{L2 - L1} \tag{3}$$

$$LAR = \frac{\ln w2 - \ln w1}{w2 - w1} \times \frac{L2 - L1}{\ln L2 - \ln L1} \tag{4}$$

where wi and Li are the total dry weight (g) and leaf area (m^2) on day ti, respectively. The days t1 and t2 are initial and last days of the growth period, respectively.

3 | RESULTS

3.1 | Gas exchange properties

(Net photosynthetic rate (A, µmol $CO_2/m^2/s$), transpiration rate (E, mmol $H_2O/m^2/s$), Stomatal conductance (S, mmol $H_2O/m^2/s$) and intercellular CO_2 concentration (Ci, mmol $H_2O/m^2/s$)).

Gas exchange properties of sorghum were generally affected by the onset of drought at terminal growth stages. Though drought stress caused noticeable reduction in leaf photosynthetic and transpiration rates, leaf photosynthetic rate at booting stage (69 DAE) decreased significantly with BF application under both normal rainfall and drought conditions (Table 2). In both drought and normal rainfall conditions, the negative association between BF supply and leaf net photosynthetic rate at boot stage appeared to be due to decreased leaf K concentration which showed steady decline with increasing BF levels (Table 2, Table 3).

Under drought, stomatal conductance increased from 0.12 mmol $H_2O/m^2/s$ at the control to 0.20 mmol $H_2O/m^2/s$ at BF2, though decreased to 0.10 mmol $H_2O/m^2/s$ at BF3, the highest BF rate. Similarly, Ci increased from 289.0 µmol CO_2/mol at the control to 327.8 µmol CO_2/mol at BF2, with a slight reduction at BF3. Generally, both stomatal conductance and intercellular CO_2 concentration increased with application of 164 kg/ha blended fertilizer. Leaf net photosynthetic rate, however, declined from 15.7 µmol $CO_2/m^2/s$ at the control to 13.4 µmol $CO_2/m^2/s$ at BF2 and 13.4 µmol $CO_2/m^2/s$ at the full dose of BF (Table 2).

The change in net photosynthetic rate due to potassium application and potassium–BF interaction was not statistically significant, at least at the time when gas exchange measurements were done. In general, net photosynthetic rate was higher in sorghum grown under normal rainfall (Figure 4; Table 2). Based on the gas exchange data (*measured at anthesis*) and all growth, yield and yield component data, the reduction in net photosynthetic rate recorded in response to BF application appears to be due to a non-stomatal limitation.

Similar to net photosynthetic rate, transpiration rate was significantly influenced by blended fertilizer application in sorghum grown both under drought and normal rainfall conditions (Figure 4; Table 2). Transpiration rate decreased from 3.65 mmol $H_2O/m^2/s$ in the control to 3.09 $H_2O/m^2/s$ at the full BF dose and from 3.81 mmol $H_2O/m^2/s$ in the control to 3.33 mmol $H_2O/m^2/s$ at the full dose, under drought and normal rainfall conditions, respectively (Table 2).

Data for stomatal conductance and intercellular CO_2 concentration of sorghum under terminal drought and normal rainfall conditions are given above in Table 2. Neither the main effects nor the interactions significantly affected leaf stomatal conductance under normal rainfall; however, the effect of blended fertilizer was significant under drought condition (Table 2). Despite the differences in statistical significance, data recorded in both drought and normal rainfall condition showed a similar increment in stomatal conductance with application of 50% of the BF. Under drought, stomatal conductance was in the range of 0.12 mmol $H_2O/m^2/s$ at the control to 0.20 $H_2O/m^2/s$ at 50% of the BF (Table 2).

Under normal rainfall condition, none of the factors significantly affected stomatal conductance ($p > .05$). However, a clear pattern of

TABLE 2 Effect of blended fertilizer application on leaf gas exchange properties in sorghum grown under normal rainfall and drought condition

	Normal Rainfall					Drought				
BF, kg/ha	AN (µmol $CO_2/m^2/s$)	E (mmol $H_2O/m^2/s$)	WUE	S (mmol H_2O/m2/s)	Ci (µmol CO_2/mol)	AN (µmol $CO_2/m^2/s$)	E (mmol $H_2O/m^2/s$)	WUE	S (mmol H_2O/m2/s)	Ci (µmol CO_2/mol)
0	18.6	3.81	4.88	0.09	67.95	15.7	3.65	4.90	0.115	289.0
164	14.2	3.37	4.37	0.64	165.17	14.6	3.26	5.08	0.196	327.8
328	13.4	3.33	4.04	0.08	114.80	13.4	3.09	5.07	0.100	296.0
$LSD_{0.05}$	1.95	0.368	0.457	NS	59.75	1.779	0.374	NS	0.083	NS
SE±	0.67	0.13	0.16	0.22	20.2	0.614	0.13	0.18	0.029	20.9

Note: NS: non-significant at $p = .05$

TABLE 3 Mean leaf potassium content and net photosynthetic rate of sorghum in response to BF supply

	Normal rainfall		Drought	
BF (kg/ha)	% K	A_N	% K	A_N
0	1.35	18.6	1.66	15.7
164	1.31	14.2	1.53	14.6
328	1.33	13.4	1.45	13.4
LSD (5%)	NS	1.95	0.153	1.77

Note: NS: non-significant at $p = .05$

increment in stomatal conductance with blended fertilizer application was observed. Values were in the range of 0.09 mmol $H_2O/m^2/s$ to 0.64 mmol $H_2O/m^2/s$, at the control and 50% of BF, respectively (Table 2).

3.2 | Water use efficiency (WUE)

WUE, calculated as a ratio of net photosynthetic rate to transpiration rate, was significantly affected only by BF application in sorghum under normal rainfall, and none of the factors were significant under drought (Table 4). Under normal rainfall, WUE decreased with increasing BF rates, from 4.87 at the control to the full BF dose. Under drought condition, on the other hand, WUE tended to increase with BF application, from 4.90 at the control to 5.08 at 50% of BF, though statistically non-significant (Table 4).

3.3 | Leaf chlorophyll content (SPAD value)

Drought stress markedly reduced relative chlorophyll concentration (SPAD value) of sorghum (Table 5). SPAD values in a range of 34.4 to 36.7 were recorded in sorghum grown under terminal drought stress, whereas under normal growing condition, SPAD values of 40.2 – 48.0 were recorded in response to BF application. Relative chlorophyll concentration of sorghum leaves under drought was 17% lower compared to the normal rainfall.

SPAD values were generally lower in sorghum plants exposed to drought than unstressed plants, but the differences among the mean values were significant for BF application ($p < .05$). Hence, under terminal drought the lowest value (34.4) was recorded at the control and the highest (36.7) was at 50% of the BF (Table 5). Despite the lack of statistical significance ($p > .05$), SPAD values ranged from around 35 at the control to 50 at the highest potassium rate (80 kg K_2O ha^{-1}) in sorghum plants supplied with potassium under normal condition (Table 5).

3.4 | Growth analysis

Under terminal drought condition, both potassium and BF affected CGR (g/m^2 day^{-1}) with some variability based on the growth stages. The analysis of variance (combined over years) indicated significant CGR (g/m^2 day^{-1}) differences among treatments, that is in response to either K, BF or K-BF interaction depending on the growth stage. The interaction effect of potassium and BF was significant at early stages (0 – 48 DAE), whereas at anthesis (48 – 69 DAE) only BF affected CGR (Table 6). Towards grain filling and maturity (69 – 90 DAE), both K and BF main effects significantly affected CGR (Table 6&7).

LAI also conforms with the idea highlighted in the above reports in that it increased with BF application, with the full dose of BF at early stages and 50% of the full dose at later stages (Figure 5). The larger LAI and its influence on the amount of radiation intercepted might have contributed much to the observed differences in crop growth rate between treatments at all growth stages. A significant similarity in the response pattern of CGR and LAI to BF application was also evident at all growth stages which further strengthens the above claims.

Under normal rainfall, the application of blended fertilizer significantly affected crop growth rate at all stages except during 48 – 69 DAE (Table 6). At this stage (48 – 69 DAE), no significant treatment effect was observed. Neither potassium nor its interaction with BF had significant effect at all growth stages. Hence, under normal rainfall, only blended fertilizer significantly influenced CGR at the beginning and final growth stages with 50% of the full BF dose consistently accompanied by the highest crop growth rates (Table 6).

It appeared that the enhancement of drought tolerance due to blended fertilizer application may be due to the higher dry matter production per unit dry weight (RGR), which in turn could be accounted for the higher assimilation rate (NAR) at the three growth stages recorded (Figure 6). In contrast to NAR recorded at different growth stages except booting (69 DAE), leaf CO_2 exchange (especially *net photosynthetic rate)* steadily declined with increasing blended fertilizer application (Table 8). A similar decline in NAR in response to BF application was also noticed at the same growth stage. While increasing BF application increased NAR in the first and last growth stages, it is unclear as to why NAR steadily decreased at booting stage (69 DAE) (Table 8).

On the other hand, comparison of data from growth analysis and gas exchange properties (*net photosynthetic rate*) measured at booting stage indicated significant similarities (Table 8). Reduction in net photosynthetic rate (A_N) and similar reduction in net assimilation rate (NAR) due to increasing BF levels was evident at the same growth stage (Table 8). Since gas exchange measurements were recorded at booting stage which coincides with the sampling stage of 69 DAE, it is highly likely that a similar pattern of increased NAR observed towards the grain filling and maturity stage (90 DAE) would be followed by gas exchange properties too, if measurements were made during this final growth stage. A strong positive association between RGR and NAR was observed at 90 DAE in drought ($R^2 = 0.82$, $p < .0001$) and normal rainfall conditions ($R^2 = 0.87$, $p < .0001$) (Figures 6 and 7).

Except at 48 DAE where BF had a significant effect, none of the treatments affected NAR (g/m^2 day^{-1}) in sorghum exposed to

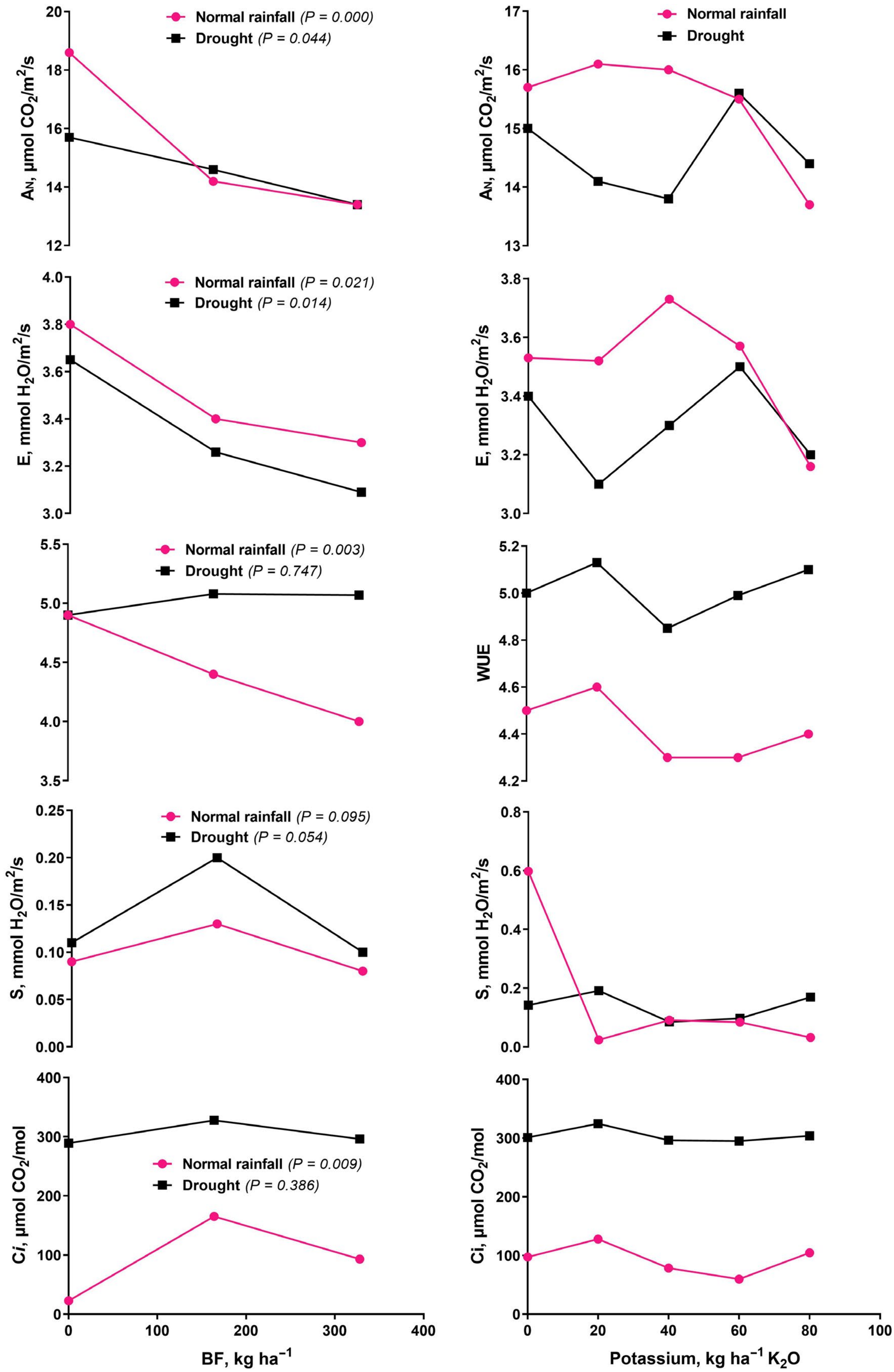


FIGURE 4 Effect of BF and K on gas exchange properties of sorghum under normal rainfall and drought conditions [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Effect of potassium and blended fertilizer application on water use efficiency of sorghum under normal and terminal drought conditions

	Water use efficiency (WUE)	
Potassium, (K_2O, kg/ha)	Normal rainfall	Drought
0	4.54	5.00
20	4.57	5.13
40	4.27	4.85
60	4.32	4.99
80	4.44	5.10
F – test	ns	Ns
Blended fertilizer (kg/ha)		
0	4.87 a	4.90
164	4.37 b	5.08
328	4.04 c	5.07
F – test	*	ns

*significant at $p = .05$, ns: non-significant at $p = .05$. Means followed by the same letter are not significantly different at $p = .05$.

TABLE 5 Effect of blended fertilizer application on leaf chlorophyll content (SPAD value) of sorghum (Data pooled over two years)

	Leaf chlorophyll content (SPAD)	
Blended fertilizer (kg/ha)	Terminal drought	Normal rainfall
0	34.4 [a]	40.2 [c]
164	36.7 [a]	44.6 [b]
328	35.4 [a]	48.0 [a]

Note: Means within column followed by the same letters are not significantly different at $p \le .05$.

terminal drought stress (Table 9). The variation observed in NAR in the first two stages (48 and 69 DAE) in response to BF application was, however, similar to that of other variables (photosynthetic rate, transpiration rate) that decreased with BF application.

Though non-significant at 5% probability, NAR at 90 DAE increased from 6.76 g/m^2 day^{-1} at the control to 10.02 g/m^2 day^{-1} at the highest BF rate (Table 10). At the same growth stage (90 DAE), potassium application significantly increased NAR from 3.31 g/m^2 day^{-1} at the control to 15.38 g/m^2 day^{-1} at K4 (60 kg/ha K_2O) (Table 10).

Based on data recorded at maturity, BF and K inputs were helpful in drought tolerance of sorghum, highlighting the contribution of potassium and nutrients in the blended fertilizer (N, P, S, Zn, B) applied at early stages and conferring benefits to the growing crop when exposed to drought stress at terminal growth stages.

3.5 | Shoot dry mass (g/m^2)

Shoot dry mass (SDM, g/m^2) of sorghum exposed to terminal drought showed a positive response to potassium and blended fertilizer

TABLE 6 Effect of blended fertilizer application on CGR (g/m^2 day^{-1}) of sorghum

	A) Drought		
BF (kg/ha)	0 – 48 DAE	48 – 69 DAE	69 – 90 DAE
0	6.84	13.98	5.48
164	9.26	18.02	15.33
328	8.75	16.81	10.54
LSD (5%)	1.19	2.879	3.54
SE±	0.42	1.016	1.25
BF (kg/ha)	B) Normal rainfall		
1	5.37	13.55	3.20
2	7.34	15.44	14.54
3	7.95	13.99	6.28
LSD (5%)	0.976	Ns	6.626
SE±	0.337	1.564	2.287

application (Table 11). SDM increased with potassium and BF application up to 40 kg/ha K_2O and 164 kg/ha BF, respectively, and decreased with application of K and BF beyond these levels (Table 11). In general, under normal rainfall, SDM response to K application varied depending on the growth period, but compared to BF the response to K was generally lower at each growth stage (Figure 8), whereas higher SDM was recorded for K than for BF at 90 DAE in sorghum exposed to terminal drought (Table 11).

In sorghum plants exposed to terminal drought in the year 2016, BF application with increasing rates resulted in steady increment of SDM at each stage with peak values attained at the highest BF rate of 328 kg/ha except at 69 DAE in which the highest SDM was witnessed in the blended fertilizer rate of 164 kg/ha (Figure 9). On the other hand, under adequate rainfall, the maximum SDM (g/m^2) recorded was recorded at 164 kg/ha BF and dropped slightly at 364 kg/ha BF at all growth stages (i.e. 48, 69 and 90 DAE) (Figure 10).

3.6 | Partitioning of dry matter into leaf, stem and panicle, g/m^2

Leaf, stem and panicle dry mass production responded positively to blended fertilizer, but no response was observed for potassium treatments (Table 12). The observed response varied at each stage of sampling and parameter depending on the growing condition, that is whether sorghum was grown exposed to terminal drought or grown without stress. Statistically significant BF effects were found only for stem dry mass at 48 and 90 DAE (Table 12). BF supply increased stem dry mass by 40% – 52% at 48 DAE and by 69% – 71% at 90 DAE (Table 12). Though not statistically significant, the variations observed in leaf and panicle dry mass due to BF application were consistent and followed a similar pattern at each stage (Table 12).

Though total shoot dry mass remained unaffected by K application, the translocation coefficients (i.e. the ratio of panicle dry weight to total dry weight) were significantly higher for potassium

TABLE 7 Effect of potassium and BF application on crop growth rate (CGR, g/m^2 day^{-1}) response of sorghum grown under terminal drought stress (at 90 DAE)

	Potassium (kg/ha, K_2O)					
BF (kg/ha)	**0**	**20**	**40**	**60**	**80**	**Mean**
0	2.69	5.32	7.82	9.17	2.41	5.48
164	10.45	11.89	17.34	19.73	17.23	15.33
328	8.53	6.73	13.24	15.32	8.90	10.54
Mean	7.22	7.98	12.80	14.74	9.51	
	Factors			LSD		
	K (*p* = .05)			4.57		
	BF (*p* = .05)			3.54		
	K * BF (*p* = .05)			ns		

Note: NS: non-significant. DAE = days after emergence

fertilizer application under drought condition (Table 13). These results highlight the positive roles of K in drought tolerance of sorghum and suggest that K supply would help to counter the impacts of drought at terminal growth stages.

4 | DISCUSSION

4.1 | Gas exchange properties

Drought-induced reduction of leaf gas exchange values was reported in several studies involving different crops and nutrients. Net photosynthetic rate decreased in rice with application of silicon (Matoh et al., 1991; Yoshida, 1981), where Si application led to a decrease in transpiration via the formation of a cuticle—silica double layer, maintaining a high leaf water potential (Matoh et al., 1991; Yoshida, 1981). Photosynthesis, stomatal conductance and transpiration decreased in drought stressed sorghum (Ali & Golombek, 2016; Massacci et al., 1996; Premachandra et al., 1995). The effect of drought stress on gas exchange at the whole plant level is often perceived as reduction in photosynthesis and growth (Cornic & Massacci, 1996).

Under normal rainfall, leaf photosynthetic rate also decreased from 18.6 µmol CO_2/m^2/s in the control to 13.4 µmol CO_2/m^2/s in the highest BF rate (328 kg/ha), while stomatal conductance increased from 0.09 mmol H_2O/m^2/s at the control to 0.64 mmol H_2O/m2/s at BF2 (164 kg/ha). On the other hand, intercellular CO_2 concentration increased from 67.9 µmol CO_2/mol at the control to 165.2 µmol CO_2/mol at BF2 (Table 2). Since the direction of *Ci* change is positive, the reduction in leaf photosynthetic rate may be due to reduction in photosynthetic activity of mesophyll cells, a non-stomatal limitation of photosynthesis (Farquhar & Sharkey, 1982).

However, Xu and Shen (2001) argued that, for many crops more than half of the economic yield is derived from photosynthesis after flowering, indicating that photosynthesis at the reproductive stage is more directly related to yield size. Hence, correlation between leaf photosynthesis and crop yield should not be expected to be positive at all stages as many photosynthetic measurements are point-in-time determinations made at varying developmental stages of the plants and do not take into consideration the entire growing season where the relationship could be masked by any of a number of biochemical and physiological events that occur between the production of photosynthates and their utilization in the accumulation of final yield (Xu & Shen, 2001). Likewise, the observed lack of positive association between net photosynthetic rate and grain yield may not be the case for all growth stages.

Though decreased transpiration rate has been documented in sorghum grown under drought (Massacci et al., 1996; Premachandra et al., 1994), fertilizer induced reduction of leaf transpiration rate

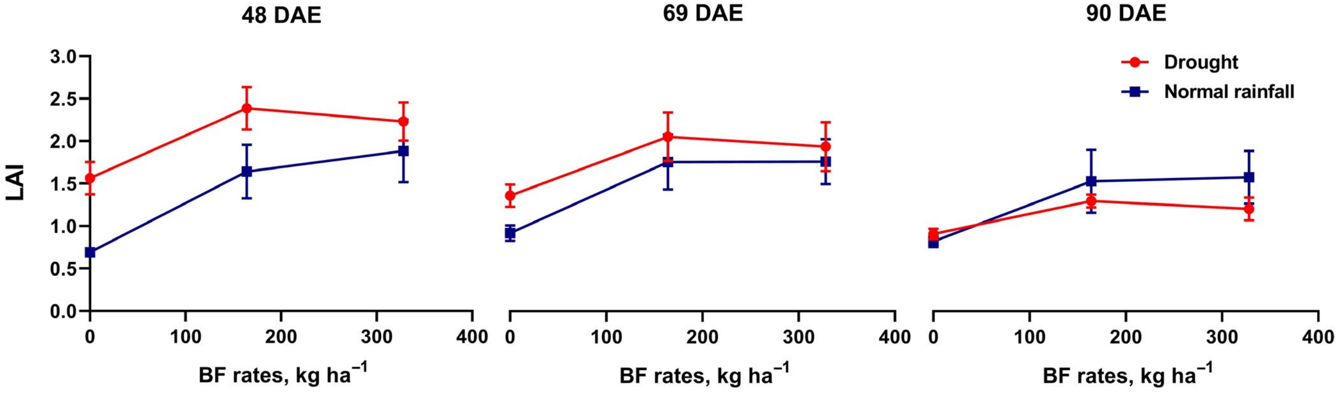


FIGURE 5 Effect of blended – NPSBZn fertilizer on LAI of sorghum at different growth stages under drought and normal rainfall conditions [Colour figure can be viewed at wileyonlinelibrary.com]

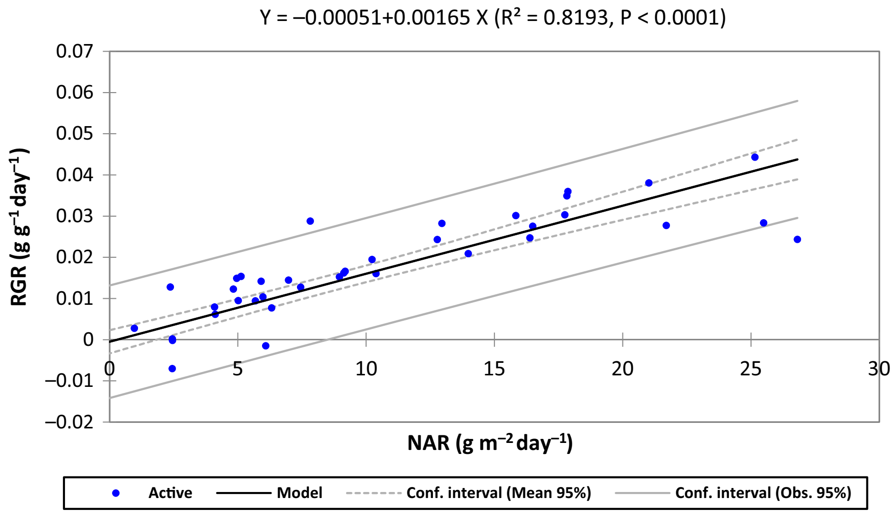


FIGURE 6 Relationship between RGR and NAR (90 DAE) in sorghum exposed to terminal drought stress. $Y = -0.00051 + 0.00165\,X$ ($R^2 = 0.8193$, $p < .0001$) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 8 Comparison of NAR (growth analysis) and Net photosynthetic rate (gas exchange) response of sorghum to BF under normal rainfall and terminal drought

Blended fertilizer (kg/ha)	NAR, g/m²/day (Drought) 48 DAE	69 DAE	90 DAE	Net photosynthetic rate (A, μmol CO_2/m²/s), 69 DAE Drought
0	14.47	**7.02**	6.76	**15.7**
164	11.42	**4.92**	8.37	**14.6**
328	11.26	**3.94**	10.02	**13.4**
BF (kg/ha)	NAR, g/m²/day (Normal rainfall)			**Normal rainfall**
	48 DAE	**69 DAE**	90 DAE	
0	7.59	20.09	4.09	**18.6**
164	5.19	10.67	9.92	**14.2**
328	4.75	10.64	4.24	**13.4**

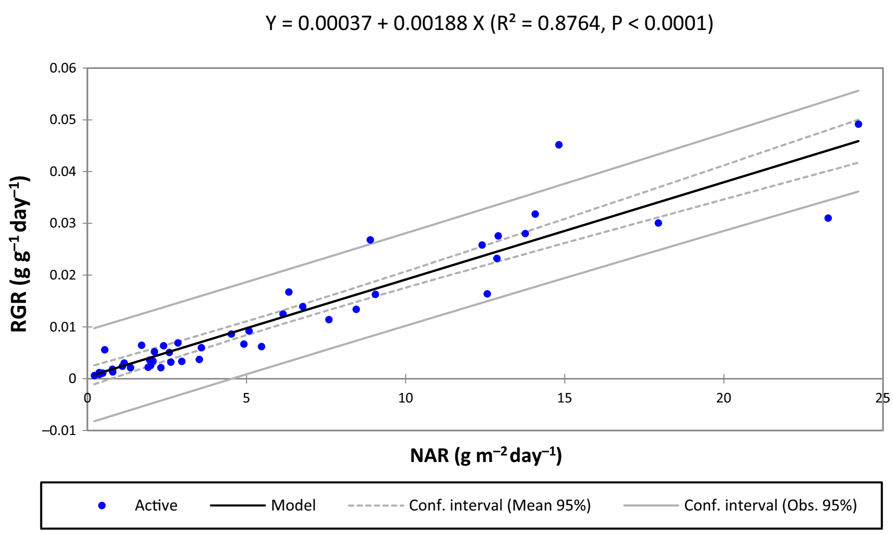


FIGURE 7 Relationship between RGR and NAR (90 DAE) in sorghum grown under normal rainfall. $Y = 0.00037 + 0.00188\,X$ ($R^2 = 0.8764$, $p < .0001$) [Colour figure can be viewed at wileyonlinelibrary.com]

has rarely been reported. The pattern of reduction observed in transpiration rate in response to BF application was similar to that of net photosynthetic rate. Though reduction in transpiration rate was observed in response to potassium in both drought and normal rainfall conditions, differences were not significant for either potassium main effect or its interaction with blended fertilizer.

In general, the reduction in leaf transpiration and net photosynthetic rate with increasing BF rates might be better clarified when taking leaf potassium concentration into consideration. Result of tissue (leaf) analysis from sorghum grown both under normal rainfall and drought conditions indicated that leaf K concentration at anthesis decreased with BF application (Table 3). As leaf (tissue) sample

TABLE 9 Effect of BF on net assimilation rate (NAR, g/m^2/day) of sorghum grown under normal rainfall and terminal drought stress

	Normal rainfall			Terminal drought		
BF (kg/ha)	48 DAE	69 DAE	90 DAE	48 DAE	69 DAE	90 DAE
0	7.59	20.09	4.09	14.4704	7.02	6.76
164	5.19	10.67	9.92	11.4161	4.92	8.37
328	4.75	10.64	4.24	11.2608	3.94	10.02
LSD	1.148	5.242	4.557	2.5859	NS	NS
SE	0.396	1.809	1.57	0.913	1.74	2.23

TABLE 10 Effect of K and BF on net assimilation rate (NAR, g/m^2/day) of sorghum under drought (90 DAE)

BF (kg/ha)	Potassium (kg/ha, K_2O)					
	0	20	40	60	80	Mean
0	0.14	0.04	17.39	14.63	1.60	6.76
164	5.41	3.11	6.44	15.74	11.13	8.37
328	4.38	7.20	10.69	15.77	12.04	10.02
Mean	3.31	3.45	11.51	**15.38**	8.26	
	Factors			LSD		
	K (p = .05)			8.144		
	BF (p = .05)			**NS**		
	K * BF (p = .05)			NS		

Note: NS: non-significant. DAE = days after emergence

TABLE 11 Effect of potassium and blended fertilizer application on total shoot dry mass (g/m^2) of sorghum exposed to terminal drought stress in 2015

	Total shoot dry mass (g/m^2)	
Potassium, (K_2O, kg/ha)	69 DAE	90 DAE
0	679.0 A	893.0
20	679.2 A	921.0
40	724.3 A	1,045.6
60	521.8 B	833.0
80	653.2 A	830.2
Blended fertilizer rate (kg/ha)		
0	592.3 a	751.0 b
164	730.5 a	1,046.8 a
328	631.7 a	915.9 a

Note: DAE: days after emergence Means within columns followed by the same letters are not significantly different at $p \le .05$.

for plant analysis and gas exchange measurements were done at the same growth stage, the observed reduction in transpiration and net photosynthetic rates with increasing BF levels appear to be associated with leaf potassium content which declined steadily in response to BF supply. Data reported by (Hirniak, 2018) indicated a similar trend of reduction in maize leaf K concentration in response to increasing nitrogen rates. Potassium deficiency is generally associated with decreased transpiration rates (Romheld & Kirkby, 2010).

Potassium influences the process of photosynthesis at many levels, namely synthesis of ATP, activation of the enzymes involved in photosynthesis, CO_2 uptake, balance of the electric charges required for photophosphorylation in chloroplasts and acting as the counter ion to light-induced H^+ flux across the thylakoid membranes (Marschner, 1995). The exact mechanisms of the effects of leaf K status on photosynthesis are still unclear; however, it has been suggested that the activity of Rubisco is an important limiting factor of photosynthesis in rice leaves (Weng et al., 2007; Yang et al., 2004). Reduced photosynthetic rate and increased Ci were also reported in cotton due to low K levels, and it was considered as an indication of a greater limitation in photosynthesis due to mesophyll conductance (Bednarz et al., 1998).

As the light-dependent uptake of K into guard cells is a critical step in stomatal opening (Shavala, 2003), it is likely that stomatal limitations may arise under K deficiency. Stomatal closure in response to K deficiency is well documented and is often considered a major factor that contributes to decreased net photosynthesis (Thiel & Wolf, 1997). However, reports from studies on different or even similar crops show much inconsistency.

Similar to stomatal conductance, intercellular CO_2 concentration (*Ci*, mmol $H_2O/m^2/s$) consistently increased with BF application up to 164 kg/ha (BF2) both under normal rainfall and drought conditions (Table 2; Figure 4). As discussed earlier, the increment of Ci with blended fertilizer application while net photosynthetic rate declined may be a strong indication of a non-stomatal limitation to photosynthesis.

Increased stomatal conductance may also be due to improved P nutrition supplied via the blended fertilizer. In a study of pearl millet, positive effects of P on plant growth under drought were attributed to an increase in stomatal conductance (Bruck et al., 2000).

4.2 | Leaf chlorophyll content (SPAD value)

Chlorophyll content under drought stress can be reduced due to the limited supply of water and nitrogen or the production of reactive oxygen species under oxidative stress that might result in the degradation of chlorophyll pigments (Lauer & Boyer, 1992). Reductions in chlorophyll content under drought stress have also been reported in other crops such as cotton (Massacci et al., 2008) and wheat (Paknejad et al., 2007).

The significant improvement in chlorophyll content of BF treated plants can be attributed to the positive role of nutrients in the blended fertilizer such as nitrogen and zinc which are actively involved in chlorophyll synthesis (Wiedenhoeft, 2006). Therefore, the present result suggests that applying BF could help prevent the negative effects of drought stress on leaf chlorophyll content.

4.3 | Crop growth rates (CGR, g/m^2 day^{-1})

Crop growth rates (CGR, g/m^2 day^{-1}) for all levels of potassium and BF reached maximum values during anthesis (48 – 69 DAE) and then

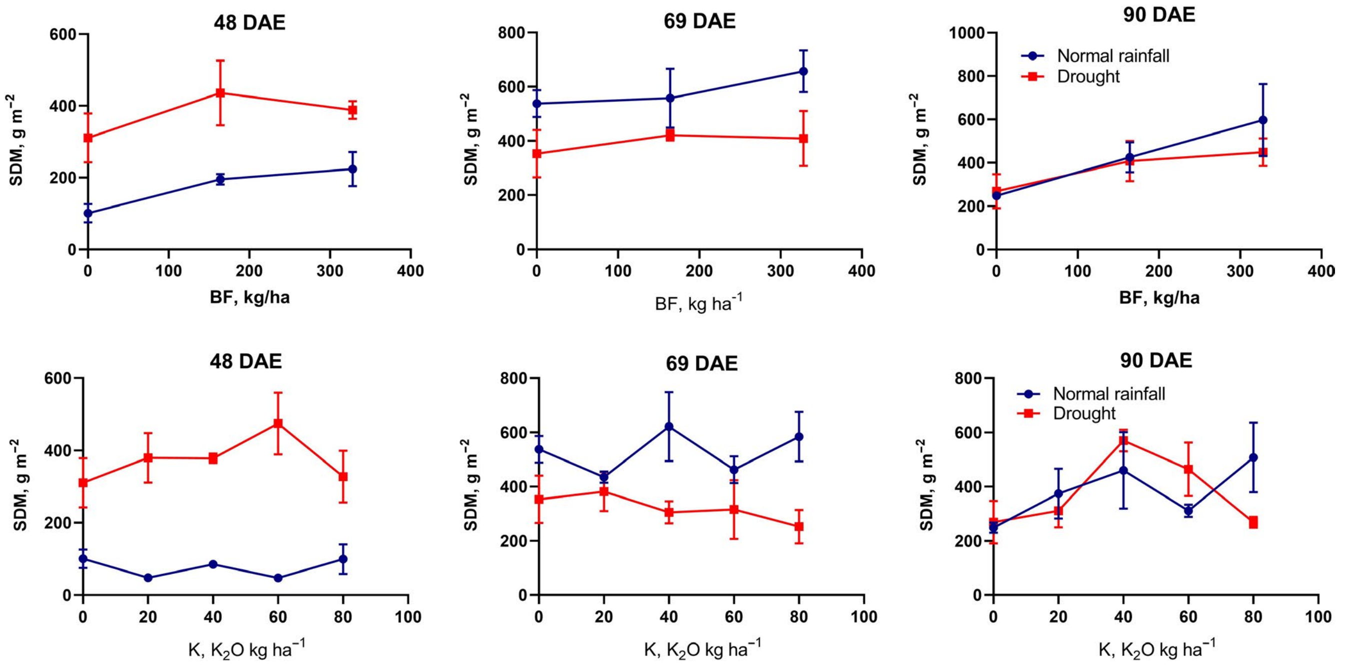
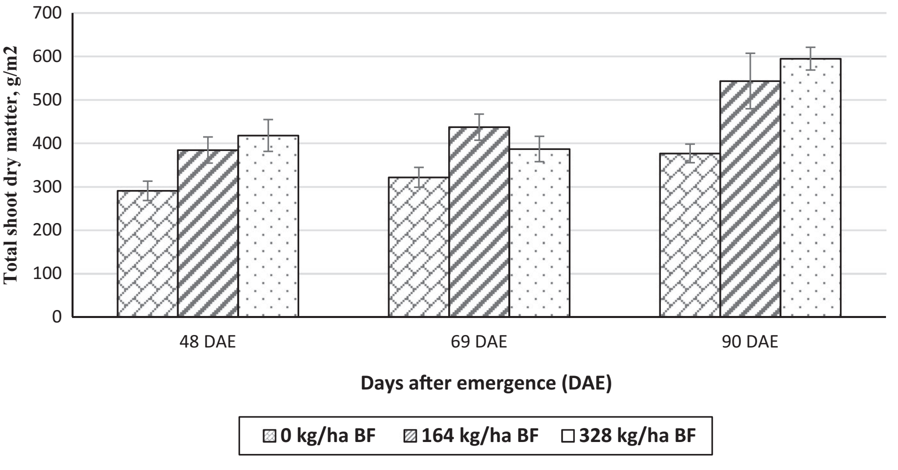


FIGURE 8 Change in shoot dry mass of sorghum due to BF and K application [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 9 Effect of blended fertilizer (averaged across potassium levels) on total shoot dry matter (g/m^2) of sorghum exposed to terminal drought stress in 2016



declined at grain filling period (69 – 90 DAE). The reduction in CGR after anthesis could be associated with a reduction in LAI due to leaf senescence. Several studies on high density maize ascribed observed increments in CGR to higher LAI (Fischer & Wilson, 1975). This assertion may be realistic as leaves in high density planting tend to be narrower and less droopy and plants become taller, features of canopy which are considered more favourable to light penetration per unit leaf area.

Several reports have described the effect of mineral nutrients on drought tolerance of different crops (Egilla et al., 2001; Liu et al., 2008; Ma et al., 2017; Marschner, 2012; Mengel et al., 2001; Nielsen & Halvorson, 1991; Oosterhuis et al., 2013; Umar, 2006; Wang et al., 2013). In terms of growth, these elements seem to achieve improvement in growth under dry conditions through the enhancement of dry matter production itself, rather than through the enhancement of properties responsible for drought tolerance (Hattori et al., 2005).

4.4 | Shoot dry mass (g/m^2) and partitioning of dry matter into leaf, stem and panicle, g/m^2

Growth, the increment in dry mass, volume, length and area, is a consequence of the interaction of processes such as photosynthesis, long-distance transport, respiration and mineral nutrition, which are all influenced directly or indirectly by soil and plant water relations (Lambers et al., 1998). Plants depend on the availability of water for growth and development and have to tightly control the internal water balance to survive under drought stress (Maurel, 1997).

The level of drought tolerance depends in most crops on the crops' development stage when the stress occurs. This adds another factor to be aware of in the characterization and study of drought tolerance (Mitchell et al., 1998). At the vegetative stage, sorghum responds to progressive drought with reductions in shoot dry matter and leaf area (Salih et al., 1999; Tsuji et al., 2003).

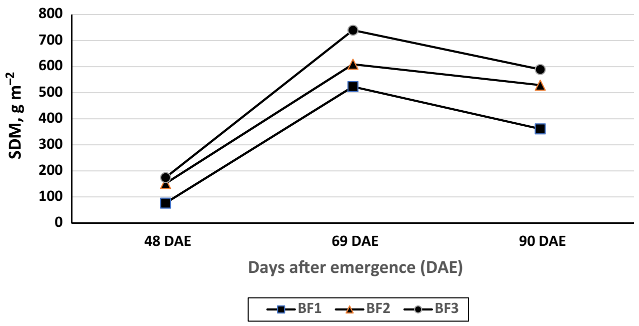


FIGURE 10 Variation in shoot dry mass (SDM) of sorghum at different growth stages in response to BF (Normal rainfall). DAE: days after emergence Means within columns followed by the same letters are not significantly different at $p \le .05$ [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 12 Effect of blended fertilizer (averaged across potassium levels) on shoot dry matter partitioning (g/m^2) of sorghum exposed to terminal drought stress

	Blended fertilizer rate (kg/ha)	dry mass (g/m^2)		
		48 DAE	69 DAE	90 DAE
Leaf	0	79.3	31.1	43.1
	164	89.1	46.0	48.8
	328	96.2	35.9	44.6
Stem	0	211.1	196.4	195.5
	164	295.3	251.2	334.0
	328	321.7	234.1	330.8
Panicle	0	-	93.9	138.0
	164	-	140.0	160.6
	328	-	116.7	219.5

Note: DAE: days after emergence. Means within columns followed by the same letters are not significantly different at $p \le .05$.

TABLE 13 Translocation coefficients of sorghum affected by K and BF inputs under normal rainfall and drought conditions

Treatments		Translocation coefficients	
K (K2O, kg/ha)	BF-NPSBZn (kg/ha)	Normal rainfall	Drought
0	0	0.24	0.16
0	164	0.32	0.26
0	328	0.33	0.39
20	0	0.39	0.36
20	164	0.28	0.33
20	328	0.35	0.34
40	0	0.26	0.34
40	164	0.33	0.31
40	328	0.26	0.29
60	0	0.43	0.41
60	164	0.31	0.26
60	328	0.31	0.39
80	0	0.44	0.43
80	164	0.26	0.28
80	328	0.38	0.39
Factors		**P values**	**P values**
K		0.655	0.007
BF		0.570	0.157
K * BF		0.703	0.254

BF application increased leaf dry mass by 12% – 21% at 48 DAE and 3% – 13% at 90 DAE (Table 12). It also increased panicle dry mass by 16% – 59% compared to the control at 90 DAE. BF application resulted in similar changes in dry mass of all other parameters at each growth stage; however except for panicle dry mass, the rate of dry matter accumulation decreased with time from the first to the last period of measurement (Table 12). Similar observations of consistently significant stem dry mass due to N fertilizer application in sorghum were reported (Bayu et al., 2002).

In sorghum grown under normal rainfall, leaf and stem dry mass accumulation increased linearly with time until anthesis and decreased markedly during grain filling (Figure 10). Part of the loss in stem and leaf dry mass after anthesis represents mobilization of labile food reserves to the seeds (Papakosta & Gagianas, 1991).

The higher leaf, stem and total dry mass with BF fertilization could be due to the positive effect of nitrogen and the other nutrients that made up the blended fertilizer (P, S, Zn and B), which might have contributed to the functioning and development of the plant in general and on canopy development as a result of alterations in leaf area development in particular. The proportion of nitrogen in the BF is much higher than that of the other nutrients (P, S, Zn and B). Plants receiving N fertilization might have larger leaf area index which can affect radiation interception and thus on photosynthetic activity of the canopy (Lugg & Sinclair, 1981 as cited by (Muchow, 1988)). Muchow and Davis (1988) also ascribed increased dry mass of sorghum and maize in response to N fertilization to higher radiation interception and radiation use efficiency.

Several researchers have reported increases in leaf, stem, panicle and total dry mass production with fertilizer application in sorghum (Martin & Kelleher, 1984; Muchow & Davis, 1988). In a study with fertilizer application and plant density, Muchow and Davis (1988) ascribed dry mass production to the interception of incident radiation by the crop canopy and the efficiency with which it is used to produce dry mass.

5 | CONCLUSION

- Application of NPSBZn-blended fertilizer and potassium significantly contributed to enhancement of drought tolerance in sorghum exposed to drought stress at terminal growth stage. The supply of nutrients (NPSBZn and potassium) at early growth (early addition of nutrients) contributed to enhancement of growth at terminal growth stages (even when exposed to drought).
- The reduced net photosynthetic rate and increased intercellular CO_2 concentration may indicate limitation of photosynthesis due

to mesophyll conductance. Plant tissue (leaf) analysis and gas exchange measurements done at the same growth stage indicated that the observed reduction in transpiration and net photosynthetic rates with increasing BF levels might be associated with leaf potassium content which also showed a steady decline in response to BF supply.

- The observed improvement in dry matter accumulation and growth due to NPSBZn-blended fertilizer and potassium both under normal rainfall and drought condition underlined the need for more nutrient (fertilizer) types in addition to the conventionally applied nitrogen and phosphorus fertilizers for sorghum.
- Therefore, supply of blended fertilizer (164 kg/ha NPSBZn-BF) and K (20 – 40 kg/ha K_2O) at early stage appeared beneficial for sorghum exposed to drought at terminal growth stage.

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