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Agronomic performance of dual-purpose *Sorghum bicolor* (L.) hybrids under water deficit

Alejandro Soares Montaño[1], Pedro Batista Rosa de Brito[1], Yohana Clara Siqueira Santana[1], Gustavo de Faria Theodoro[1*], Fernando França da Cunha[2]

[1]Fundação Universidade Federal de Mato Grosso do Sul – Faculdade de Medicina Veterinária e Zootecnia, Av. Sen. Filinto Müler, 2443 - Pioneiros, Campo Grande - MS, 79070-900, Brazil
[2]Universidade Federal de Viçosa - Departamento de Engenharia Agrícola, Av. Peter Henry Rolfs, s/n - Campus Universitário, Viçosa - MG, 36570-900, Brazil

***Corresponding author: gustavo.theodoro@ufms.br**

Abstract

This study aimed to assess the agronomic performance of five sorghum hybrids irrigated with two replacement levels of crop evapotranspiration (ETc). The experimental design was randomized blocks in a 5x2 factorial scheme with four replications. The factors were dual-purpose sorghum hybrids (AGRI 002-E, AGRI G1, AGRI G2, BREVANT SS318 and BRS 58) and water replacement levels (50% and 100% of ETc). The replacement of 50% of ETc was defined as water deficit (WD). The experiment was conducted in a greenhouse, and sorghum was grown in pots. The mean comparison test showed that plants under WD condition had low values of height, stem diameter, leaf area, chlorophyll content, and a 37% reduction in shoot dry mass productivity. The analysis of principal components revealed that the correlations between the variables changed according to the water regimes. Under WD, water productivity, shoot dry mass, and leaf area index were highly correlated with each other and with the hybrid AGRI 002-E. The hybrid AGRI 002-E showed better performance under normal irrigation conditions, while under WD conditions, the hybrids BREVANT SS318 and BRS 658 also showed good performance. Hybrids with higher leaf area and water productivity performed better under water-scarcity conditions.

Keywords: biomass; silage; irrigation; tolerance; sustainability.

Abbreviations: AUPCCHLi_area under the chlorophyll index progress curve; AUPCLAI_area under the leaf area index progress curve; CHLi_chlorophyll index; CV_ coefficient of variation; DAE_days after emergence; DM_shoot dry mass; ETc_ crop evapotranspiration; FM_shoot fresh mass; HBD_hybrids; LAI_leaf area index; PCA_ principal component analysis; PH_plant height; RM_root dry mass; SD_stem diameter; WD_water deficit; WP_water productivity.

Introduction

In tropical countries food security may be threatened due to WD, which frequently limits the productivity of agricultural and forage crops (Marengo et al., 2022), especially taking into account reports of climate change (Shortridge, 2019; Perera et al., 2020)

However, it is important to acknowledge that there is significant variability in the tolerance of plants to WD, even within the same species. This inherent diversity presents promising opportunities for the utilization of these plants by farmers and in breeding programs (Abreha et al., 2022).

Sorghum (*Sorghum bicolor* L.) exhibits a remarkable versatility that renders it suitable for feed (Tiritan et al., 2013; Getachew et al., 2016; Rezende et al., 2020) and food (Awika and Rooney, 2004; Queiroz et al., 2011). Its nutritional composition allows for inclusion in gluten-restricted diets and utilization as a bioactive ingredient, making it particularly valuable in the diets of individuals facing socioeconomic vulnerability (Adebo, 2020).

The rusticity attributed to sorghum suggests tolerance to WD (Widodo et al., 2023), but there is evidence that under these conditions the plant development and yield can be seriously reduced (Batista et al., 2020; Souza et al., 2021). Due to the existence of sorghum hybrids with varying aptitudes or purposes and, as a result, differences in morphology, ecophysiology, and growth habits (Theodoro et al., 2021a; Bozal-Leorri et al., 2023), generalized recommendations for sorghum crop may lack accuracy.

In the Brazilian Semiarid, Menezes et al. (2022) studied the imposition of WD before and after flowering on 20 grain sorghum hybrids and concluded that only five showed the highest productivity. Under controlled conditions, Munamava and Riddoch (2001) did not find significant differences between three grain sorghum cultivars subjected to WD. However, the WD caused a reduction in the total leaf area and productivity when the panicle was developed, but still inserted in the sheath of the last leaf.

Tsuji et al. (2003) conducted a field study to assess the behavior of three sorghum cultivars under irrigation suppression. They found that the Gadambalia cultivar demonstrated tolerance to WD, which was attributed to its smaller leaf area, higher liquid water flow conductance, and ability to maintain high leaf water potential.

According to Gano et al. (2021) growth speed and an increased root volume were associated with the adaptation of sorghum cultivars to WD conditions in West Africa. Batista (2020) related average productivity, geometric average productivity and average relative performance as selection indices for grain sorghum, however, studies with no-grain sorghum are scarce.

The aim of this paper was to evaluate the agronomic performance of five dual-purpose sorghum hybrids under WD, by analyzing morphological traits, chlorophyll index and biomass yield parameters.

Results and discussion

Plants that received 100% replacement of ETc had a water consumption of 41.54 L pot^{-1}. On the other hand, for the 50% ETc treatment, where plants received half of the water replacement from 33 DAE, the volume of water applied was 26.23 L pot^{-1}.

Considering the effect of water replacement on the height of sorghum hybrids (Table 1), there was a significant interaction ($p \leq 0.05$) between the factors in the evaluations performed at 39, 46 and 90 DAE. It can be seen that there was variation in the behavior of the hybrids as a function of the water supply and their stage of development. At 90 DAE, all hybrids showed a decrease in height when subjected to 50% ETc replacement, but only AGRI 002-E (39, 46, and 90 DAE) and AGRI G1 (39 and 90 DAE) displayed a reduction in height in previous evaluations as well.

This reduction in sorghum height caused by WD implies an immediate loss of fresh and dry matter (Gonulal, 2020). Only two hybrids, AGRI 002-E and AGRI G1, showed a reduction in height in previous evaluations as well, indicating that these hybrids are probably more susceptible to water stress throughout their development. This information can be valuable for selecting sorghum hybrids that are more tolerant to water stress, which is essential for ensuring crop yield under varying environmental conditions.

At 53 DAE, sorghum plants subjected to 50% of the crop water requirement (ETc) exhibited a 27.08% reduction ($p \leq 0.05$) in height compared to those irrigated with 100% of ETc. At 90 DAE, taller heights were recorded for the BREVANT SS318 and BRS 658 sorghum hybrids irrigated with 100% of ETc. However, under WD conditions, only the BRS 658 plants showed higher height, averaging at 87.25 cm. These results align with previous findings by Mantoan et al. (2020), who demonstrated that stomatal closure in response to WD minimizes leaf water losses, reduces gas exchange, and ultimately results in lower carbon incorporation into the biomass.

Water replacement levels and hybrids did not significantly affect sorghum stem diameter at 39 and 89 DAE, as indicated in Table 2. However, at 46 DAE, WD led to a 10.5% reduction in stem diameter for the sorghum hybrids evaluated. A significant interaction between the factors for stem diameter ($p \leq 0.05$) was only observed at 53 DAE. Specifically, the hybrid AGRI G1 displayed a smaller stem diameter when receiving 100% ETc replacement, but no difference was observed under WD conditions. In contrast, WD did not reduce stem diameter for the AGRI G1 and BRS 658 hybrids, suggesting a hybrid-dependent response that warrants further investigation. Kirchner et al. (2020) demonstrated that stem diameter and plant height are reduced under WD, which may compromise the quality of roughage used for animal production.

Table 3 shows that water replacement levels only influenced the LAI of sorghum hybrids from 54 DAE onwards. At this stage, a significant interaction between the factors was observed, with the AGRI 002-E, BREVANT SS318, and BRS 658 hybrids exhibiting lower LAI values under WD treatment. In the subsequent evaluation, only the effect of water replacement levels was observed, and LAI was 22.89% lower under WD.

At 54 DAE, LAI was similar in hybrids subjected to WD, but compared to those receiving 100% ETc replacement, the AGRI 002-E, BREVANT SS318, and BRS 658 hybrids displayed reduced LAI values. At 90 DAE, individual effects of factors on LAI were observed (Table 3), with the AGRI 002-E and BREVANT SS318 hybrids showing the largest leaf area of 509.22 and 302.48, respectively.

Temporal analysis of LAI using the AUPCLAI method did not indicate any differences between the hybrids. Only water replacement levels contributed to the reduction in plant leaf area over time. As area calculation depends on each evaluation moment, these data were influenced by the absence of LAI response to treatments in the first two evaluations (39 and 46 DAE).

In a field evaluation of twenty grain sorghum hybrids at different growth stages, Batista et al. (2020) reported that plants from the control treatment at 60 days after sowing had a higher LAI than those from the WD treatment. Moreover, after 60 and 90 days after sowing, the authors observed that plants under WD exhibited lower growth compared to well-irrigated plants.

The CHLi of sorghum was not affected by an interaction between hybrids and water replacement levels at any evaluated time (Table 4). Nonetheless, differences between hybrids were noted from the first evaluation (38 DAE), while significant effects of water replacement levels on the plants were observed from 52 DAE. This observation is due to the fact that the plants were subjected to both water regimes from 33 DAE onwards. Moreover, the soil used in the experiment had a high water retention capacity, possibly contributing to this result (Delage and Tessier, 2021).

The CHLi of plants subjected to WD (50% of ETc) decreased by 6.04% (52 DAE), 6.64% (58 DAE), and 6.87% (82 DAE). This reduction in chlorophyll concentration was also noted in sorghum plants exposed to WD by Matos et al. (2021) and is believed to occur as a photoprotection mechanism of photosynthesis (Hippler et al., 2021).

AGRI 002-E had the lowest CHLi in its leaves during the first three evaluations (38, 47, and 52 DAE). Conversely, AGRI G1 and AGRI G2 had the highest CHLi from 52 DAE onwards.

By analyzing the area under the curve of the CHLi values, which accounts for potential fluctuations over the evaluation period, the hybrids can be categorized according to their CHLi levels. The hybrids with lower CHLi were AGRI 002-E, while BREVANT SS318 and BRS 658 showed intermediate CHLi levels. On the other hand, AGRI G1 and AGRI G2 displayed higher CHLi levels. In line with the separate evaluations, a significant reduction of 5.88% in CHLi was observed during the WD imposition period ($p \leq 0.05$).

Fresh mass productivity (FM) of the aerial part of sorghum showed a significant interaction between the factors (Table

5). When the plants were given 100% ETc replacement, AGRI 002-E was found to be the most productive hybrid. Hybrids BREVANT SS318 and BRS 658 grouped together and produced more FM than the third cluster, which consisted of AGRI G1 and AGRI G2 hybrids. Under WD, only two clusters of hybrids were observed. The first group was represented by hybrids with the highest FM productivity per pot (AGRI 002-E, BREVANT SS318, and BRS 658), while the second group was made up of hybrids that produced less FM (AGRI G1 and AGRI G2). However, the hybrids produced similar amounts ($p > 0.05$) of dry mass per pot, and a significant effect of HBD on this variable was observed. Despite sorghum being known to be a robust and WD-tolerant species, the reduction in dry mass of plants under 50% ETc replacement was approximately 37%.

The significant interaction between water replacement levels and hybrids on FM (Table 5) highlights the importance of considering the genotype and environmental interaction in plant breeding and crop management. The fact that different hybrids performed differently under different water regimes emphasizes the need to select genotypes that are better adapted to the environmental conditions in which they will be grown. This approach can lead to the development of more drought-tolerant cultivars, which will be particularly important in regions prone to water scarcity.

The reduction in biomass productivity under severe water stress can be attributed to stomatal closure, which results in the decrease in fresh and dry biomass accumulation. However, this negative impact can be mitigated by employing drought-tolerant genotypes, as suggested by previous studies (Santos et al., 2014; Li et al., 2022). The analysis of dry matter content (%) revealed a significant effect of the hybrid factor ($p \leq 0.05$), with AGRI G1 and AGRI G2 exhibiting higher dry matter contents due to their late harvesting. Despite the late harvest, AGRI G2 still had dry matter content levels suitable for silage. The other sorghum hybrids exhibited dry matter contents falling within the recommended range for silage, and their performance remained unaffected by variations in water replacement levels.

Table 5 shows that there was no significant difference between treatments in terms of WP. This result can be explained by the fact that the reduction in water availability in the different treatments was accompanied by a decrease in sorghum biomass productivity at the same intensity. The hybrids exhibited similar behavior in relation to the amount of water required to produce a unit of dry mass. Although this study did not compare sorghum with other grain species of the same agricultural interest, it is possible that WP may be a differential factor in the selection of sorghum under water-limited conditions.

Regarding the root system analysis, a significant interaction was observed between the factors for FM data, indicating that only AGRI G1 and BREVANT SS318 hybrids did not show a reduction in this variable under WD (Supplementary table 1). However, the dry mass and dry matter content did not differ between treatments, indicating the need to also evaluate the volume of the root system of plants subjected to different levels of water restriction.

Based on the experimental conditions described in this study, it is recommended that evaluations of sorghum hybrid morphological characteristics should be conducted 20 days after the imposition of WD. Evaluations performed at different times may result in divergent results regarding hybrid performance. Therefore, the use of the areas under the progress curve for leaf area and chlorophyll indices is recommended as these parameters are not affected by the evaluation time.

Principal component analysis was utilized to assess the performance of sorghum hybrids from a multivariate perspective, taking into account the combined effects of all variables (Figure 1). The PCA analysis was validated by Chaves et al. (2023), who performed a comparable experiment involving corn for silage. Their results indicated a more reliable identification of WD-tolerant genotypes when employing PCA as opposed to univariate analysis.

Two were selected among five PCs because explained 95.8% (PC1) and 84.5% (PC2) of the total variance in the data (Supplementary tables 2 and 3), respectively, when the plants were grown with 100% and 50% ETc replacement (Silva and Sbrissia, 2010). The correlation between the correlation matrix of the data with the principal components revealed the significance of each variable. When the hybrids were subjected to 100% ETc replacement, the most significant variables for the first principal component (PC1), which accounted for 57.2% of the data variance, were LAI, FM, RM, DM, WP, PH and CHLi. In the second principal component (PC2), which explained 38.6% of the variance, the most important variables were SD, PH, LAI, FM and WP.

The acute angles formed by LAI, FM, and RM variables indicate high correlation, as reported by Hongyu et al. (2016). Similarly, DM and WP variables showed a strong correlation, whereas low correlations were observed between DM, WP, SD, FM, RM, and LAI (Figure 1-A). Under full water supply, the sorghum hybrids displayed distinct behavior patterns. AGRI 002-E was positively correlated with LAI, FM, and RM in PC1. In PC2, BREVANT SS318 and BRS 658 were grouped together with the WP variable, indicating their high relevance as hybrids that use water more efficiently.

In contrast, these hybrids exhibited a weak correlation with LAI, suggesting that higher FM productivity and larger leaf areas in forage sorghum hybrids may be negatively associated with WP. This finding implies that if the leaf area is larger, there will be a greater loss of water through transpiration by the plants, unless there is an effective and efficient mechanism to offset this phenomenon. In summary, these results suggest that WP and LAI should be taken into account simultaneously when evaluating the performance of forage sorghum hybrids under water-limited conditions (Fardin et al., 2023).

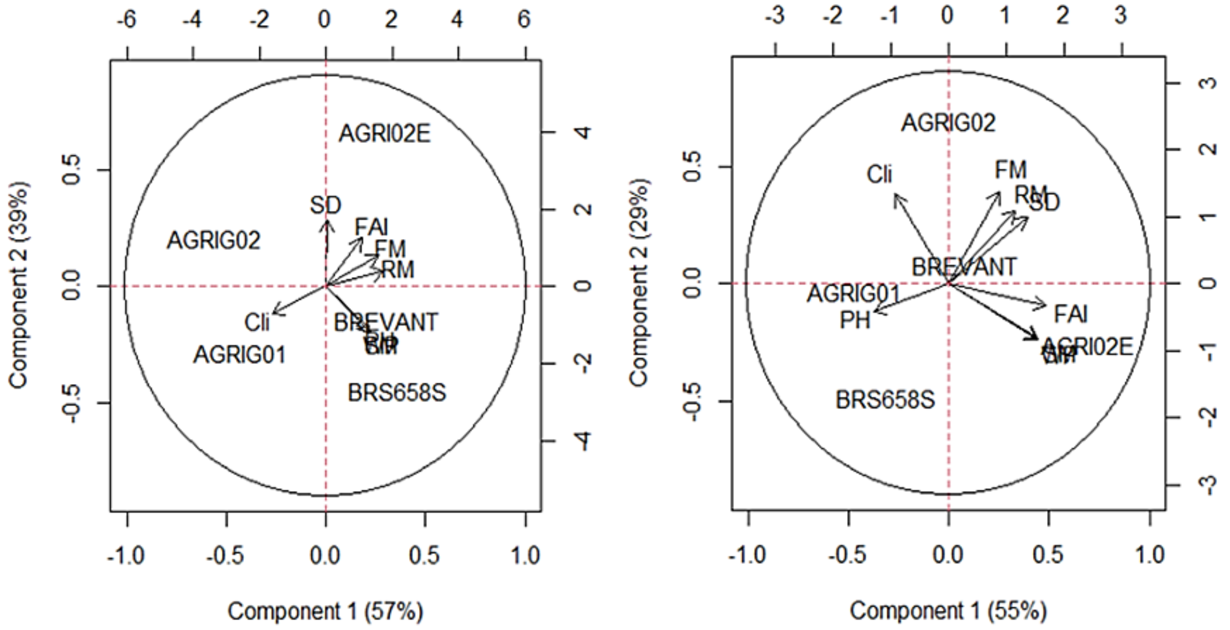
AGRI G2 was the least performing hybrid under normal water supply conditions, as it exhibited the lowest WP and poor correlation with FM in PC1. Similarly, AGRI G1, despite showing high correlation with the highest CHLi, was positioned in an inverse quadrant to the variables LAI, FM, and RM. These results are significant because the hybrids displayed unfavorable attributes for producing silage. The findings of the study reveal the significance of WP and FM productivity as crucial factors for determining the performance of sorghum hybrids under WD conditions. AGRI G2's poor performance under normal water supply conditions could indicate that it may be more susceptible to water stress compared to other hybrids. Similarly, AGRI G1's unfavorable attributes, despite showing high correlation with CHLi, suggests that the hybrid may not be ideal for silage production.

The results of the analysis conducted on plants grown with 50% ETc replacement showed that PC1 accounted for 55% of the data variance and the variables SD, PH, LAI, DM, RM, and WP were the most significant. In contrast, PC2 explained

Table 1. Sorghum height (cm) values for different days after emergence (DAE) and as a function of hybrids (HBD) and water replacement levels (WRL, %ETc).

CV (%)	*p*-valor			HBD	WRL (%ETc)		Mean
	WRL	HBD	WRL *HBD		100	50	
------------------------ 39 DAE ------------------------							
12.0	0.3488	0.2153	0.0125	AGRI 002-E	32.83^{Aa}	25.33^{Bb}	29.08
				AGRI G1	26.38^{Aa}	32.15^{Ab}	29.26
				AGRI G2	31.33^{Aa}	32.50^{Aa}	31.91
				BREVANT SS318	28.55^{Aa}	26.75^{Ba}	27.65
				BRS 658	30.45^{Aa}	27.48^{Ba}	28.96
				Mean	29.91	28.84	
------------------------ 46 DAE ------------------------							
9.3	0.0204	0.0171	0.0499	AGRI 002-E	32.78^{Aa}	28.18^{Bb}	30.48
				AGRI G1	31.20^{Aa}	33.85^{Aa}	32.53
				AGRI G2	35.20^{Aa}	34.60^{Aa}	34.90
				BREVANT SS318	31.33^{Aa}	28.50^{Ba}	29.91
				BRS 658	34.25^{Aa}	28.13^{Bb}	31.19
				Mean	32,95	30,65	
------------------------ 53 DAE ------------------------							
16.1	<0.001	0.6693	0.1724	AGRI 002-E	40.88	29.48	35.18
				AGRI G1	38.75	36.38	37.56
				AGRI G2	43.35	29.20	36.28
				BREVANT SS318	41.80	29.15	35.47
				BRS 658	47.58	30.60	39.09
				Mean	42.47^{a}	30.96^{b}	
----------------------- 90 DAE ------------------------							
				AGRI 002-E	92.43^{Ba}	55.38^{Bb}	73.90
				AGRI G1	90.00^{Ba}	69.63^{Bb}	79.81
15.5	<0.001	<0.001	<0.001	AGRI G2	86.00^{Ba}	70.63^{Bb}	78.31
				BREVANT SS318	133.75^{Aa}	59.13^{Bb}	96.44
				BRS 658	143.25^{Aa}	87.25^{Ab}	115.25
				Mean	109.09	68.40	

Means followed by the same lowercase letter in the row and uppercase in the column do not differ from each to the Scott–Knott test at 5% probability. CV: coefficient of variation.



(a) (b)

Figure 1. Biplot of the first (x-axis) and second (y-axis) principal components referring to the five sorghum hybrids cultivated with replacement of 100% (a) and 50% (b) of crop evapotranspiration. SD: stem diameter; PH: plant height; LAI: leaf area index; CHLi: chlorophyll index; FM: shoot fresh mass; DM: shoot dry mass; RM: root dry mass; WP: water productivity.

Table 2. Sorghum stem diameter (mm) values for different days after emergence (DAE) and as a function of hybrids (HBD) and water replacement levels (WRL, %ETc).

CV (%)	*p*-valor			HBD	WRL (%ETc)		Mean
	WRL	HBD	WRL*HBD		100	50	
----------------------- 39 DAE -----------------------							
23.4	0.8867	0.2999	0.1655	AGRI 002-E	15.61	11.43	13.52
				AGRI G1	12.48	15.26	13.87
				AGRI G2	15.90	14.97	15.43
				BREVANT SS318	15.43	13.43	14.43
				BRS 658	15.20	18.75	16.97
				Mean	14.92	14.77	
----------------------- 46 DAE -----------------------							
11.0	<0.001	0.4881	0,0511	AGRI 002-E	16.84	12.63	14.74
				AGRI G1	14.81	15.72	15.27
				AGRI G2	16.89	15.56	16.22
				BREVANT SS318	16.92	14.71	15.81
				BRS 658	17.06	13.67	15.36
				Mean	16.50^{a}	14.76^{b}	
----------------------- 53 DAE -----------------------							
9.8	0.0012	0.7437	0.0279	AGRI 002-E	20.03^{Aa}	15.53^{Ab}	17.78
				AGRI G1	16.69^{Ba}	18.23^{Aa}	17.46
				AGRI G2	19.88^{Aa}	17.23^{Ab}	18.55
				BREVANT SS318	19.74^{Aa}	16.86^{Ab}	18.30
				BRS 658	19.02^{Aa}	17.41^{Aa}	18.21
				Mean	19.07	17.05	
----------------------- 89 DAE -----------------------							
				AGRI 002-E	19.26	16.78	17.67
				AGRI G1	15.29	15.29	15.29
14.5	0.0572	0.0923	0.7454	AGRI G2	18.30	16.53	17.41
				BREVANT SS318	16.59	15.58	16.09
				BRS 658	15.59	14.18	14.88
				Mean	17.01	15.53	

Means followed by the same lowercase letter in the row and uppercase in the column do not differ from each to the Scott–Knott test at 5% probability. CV: coefficient of variation.

Table 3. Leaf area index (cm²) and area under the progress curve of leaf area index (AUPCLAI) for different days after emergence (DAE) and as a function of hybrids (HBD) and water replacement levels (WRL, %ETc).

CV (%)	*p*-valor			HBD	WRL (%ETc)		Mean
	WRL	HBD	WRL *HBD		100	50	
----------------------- 39 DAE -----------------------							
21.6	0.6303	0.7645	0.1145	AGRI 002-E	275.65	203.94	239.79
				AGRI G1	169.16	222.33	195.74
				AGRI G2	148.33	212.38	180.01
				BREVANT SS318	189.07	197.66	193.36
				BRS 658	230.28	135.74	183.01
				Mean	202.49	194.41	
----------------------- 46 DAE -----------------------							
13.2	0.1877	0.3945	0.4983	AGRI 002-E	333.11	307.70	320.41
				AGRI G1	251.20	297.88	274.54
				AGRI G2	331.64	260.85	296.24
				BREVANT SS318	274.73	215.52	245.12
				BRS 658	271.97	239.31	255.64
				Mean	292.53	264.25	
----------------------- 54 DAE -----------------------							
10.1	<0.001	0.2901	0.0340	AGRI 002-E	446.96^{Ba}	308.01^{Ab}	377.48
				AGRI G1	378.72^{Ba}	394.06^{Aa}	386.39
				AGRI G2	434.96^{Ba}	355.07^{Aa}	395.01
				BREVANT SS318	568.79^{Aa}	359.19^{Ab}	463.99
				BRS 658	531.58^{Aa}	293.68^{Ab}	412.63
				Mean	472.20^{a}	342.00^{b}	
----------------------- 90 DAE -----------------------							
				AGRI 002-E	553.76	464.68	509.22^{A}
				AGRI G1	230.14	153.08	191.61^{C}
				AGRI G2	183.92	173.51	178.72^{C}
11.9	<0.001	<0.001	0.4025	BREVANT SS318	332.82	272.14	302.48^{B}
				BRS 658	246,00	129.14	187.57^{C}
				Mean	309.33^{a}	238.51^{b}	

------------------------ AUPCLAI ------------------------							
				AGRI 002-E	8753.40	6957.92	7855.66
				AGRI G1	6121.89	6503.34	6312.62
8.8	<0.001	0.0999	0.0844	AGRI G2	6912.32	5970.02	6441.17
				BREVANT SS318	8152.93	5954.57	7053.75
				BRS 658	7693.54	4924.45	6308.99
				Mean	7526.82^{a}	6062.06^{b}	

Means followed by the same lowercase letter in the row and uppercase in the column do not differ from each to the Scott–Knott test at 5% probability. CV: coefficient of variation.

The chlorophyll index (CHLi) of sorghum was not affected by an interaction.

Table 4. Chlorophyll index (CHLi) and area under the progress curve of chlorophyll index (AUPCCHLi) for different days after emergence (DAE) and as a function of hybrids (HBD) and water replacement levels (WRL, %ETc).

CV (%)	*p*-valor			HBD	WRL (%ETc)		Mean
	WRL	HBD	WRL *HBD		100	50	
------------------------ 38 DAE ------------------------							
7.2	0.2340	0.0116	0.6514	AGRI 002-E	44.19	40.78	42.49^{B}
				AGRI G1	45.93	47.58	46.76^{A}
				AGRI G2	49.48	48.15	48.82^{A}
				BREVANT SS318	46.53	44.84	45.68^{A}
				BRS 658	46.02	44.50	45.26^{A}
				Mean	46.48	45.20	
------------------------ 47 DAE ------------------------							
7.0	0.0647	<0.001	0.8890	AGRI 002-E	41.96	39.50	40.73^{B}
				AGRI G1	48.60	48.87	48.38^{A}
				AGRI G2	49.43	45.87	47.65^{A}
				BREVANT SS318	47.62	45.60	46.61^{A}
				BRS 658	46.51	45.29	45.90^{A}
				Mean	46.82	44.88	
------------------------ 52 DAE ------------------------							
7.3	0.0115	<0.001	0.5673	AGRI 002-E	42.88	38.84	40.86^{C}
				AGRI G1	50.41	47.91	49.16^{A}
				AGRI G2	47.50	47.95	47.72^{A}
				BREVANT SS318	47.96	43.12	45.54^{B}
				BRS 658	46.58	43.23	44.91^{B}
				Mean	47.06^{a}	44.21^{b}	
------------------------ 58 DAE ------------------------							
				AGRI 002-E	44.34	42.68	43.51^{B}
				AGRI G1	51.31	48.93	51.31^{A}
9.8	0.0365	0.0239	0.9053	AGRI G2	49.03	48.38	49.03^{A}
				BREVANT SS318	47.11	44.77	47.11^{B}
				BRS 658	45.71	43.84	45.71^{B}
				Mean	48.95^{a}	45.7^{b}	
------------------------ 82 DAE ------------------------							
				AGRI 002-E	48.86	43.87	46.36^{B}
				AGRI G1	57.70	55.71	56.71^{A}
8.2	0.0107	<0.001	0.5112	AGRI G2	56.11	56.06	56.08^{A}
				BREVANT SS318	51.54	47.40	49.47^{B}
				BRS 658	51.54	45.00	48.58^{B}
				Mean	53.27^{a}	49.61^{b}	
------------------------ AUPCCHLi ------------------------							
				AGRI 002-E	2196.49	2041.48	2118.99^{C}
				AGRI G1	2577.14	2458.47	2517.80^{A}
6.3	0.0052	<0.001	0.6203	AGRI G2	2491.23	2438.14	2464.68^{A}
				BREVANT SS318	2408.34	2218.90	2313.62^{B}
				BRS 658	2362.85	2171.66	2267.26^{B}
				Mean	2407.21^{a}	2265.73^{b}	

Means followed by the same lowercase letter in the row and uppercase in the column do not differ from each to the Scott–Knott test at 5% probability. CV: coefficient of variation.

Table 5. Values of fresh mass (FM), dry mass (DM) and dry matter content of shoots and water productivity (WP) of sorghum as a function of hybrids (HBD) and water replacement levels (WRL).

CV (%)	*p*-valor			HBD	WRL (%ETc)		Mean
	WRL	HBD	WRL *HBD		100	50	
------------------------ Fresh mass (g pot^{-1}) ------------------------							
10.0	<0.001	<0.001	<0.001	AGRI 002-E	301.80^{Aa}	123.10^{Ab}	212.78
				AGRI G1	89.50^{Ca}	63.00^{Ba}	76.25
				AGRI G2	102.46^{Ca}	82.71^{Ba}	92.58
				BREVANT SS318	268.23^{Ba}	124.10^{Ab}	196.16
				BRS 658	234.98^{Ba}	119.45^{Ab}	177.21
				Mean	199.39	102.60	
------------------------ Dry mass (g pot^{-1}) ------------------------							
14.1	<0.001	0.3724	0.4269	AGRI 002-E	45.10	37.90	41.49
				AGRI G1	47.20	25.84	36.52
				AGRI G2	38.21	28.05	33.13
				BREVANT SS318	53.10	29.20	41.15
				BRS 658	57.90	30.73	44.31
				Mean	48.30^{a}	30.41^{b}	
------------------------ Dry matter content (%) ------------------------							
16.4	0.4228	<0.001	0.1644	AGRI 002-E	15.50	30.75	23.13^{B}
				AGRI G1	53.13	42.16	47.64^{A}
				AGRI G2	37.06	34.45	35.76^{A}
				BREVANT SS318	19.55	23.51	21.53^{B}
				BRS 658	24.67	25.76	25.21^{B}
				Mean	29.98	31.33	
------------------------ Water Productivity (g L^{-1}) ------------------------							
8.1	0.9157	0.4583	0.5218	AGRI 002-E	1.09	1.44	1.27
				AGRI G1	1.14	0.98	1.06
				AGRI G2	0.92	1.06	0.99
				BREVANT SS318	1.28	1.11	1.19
				BRS 658	1.39	1.17	1.28
				Mean	1.16	1.15	

Means followed by the same lowercase letter in the row and uppercase in the column do not differ from each to the Scott–Knott test at 5% probability. CV: coefficient of variation.

only 29.5% of the variance and the variables SD, CHLi, FM, DM, RM, and WP were the most representative. The variables WP, DM, and LAI showed a strong correlation with each other but had little correlation with FM, RM, and SD.

The results of the study indicate that some sorghum hybrids that exhibit the best performance under WD conditions are those that produce more LAI while consuming less water. This observation is consistent with WP theory and previous research that has demonstrated the importance of traits related to water-use efficiency, such as reduced stomatal conductance and increased root biomass, in improving plant performance under limited water availability (Ludlow and Muchow, 1990). The association between an expanded leaf area and efficient water use in sorghum can be elucidated by the fact that shoot biomass is the main variable related to yield (Bhattarai et al., 2020). Additionally, given its African provenance, sorghum is endowed with a suite of adaptive mechanisms that ameliorate the detrimental impacts of water scarcity (Obgaba et al., 2014; Hao et al., 2021). These findings underscore the heightened efficiency of sorghum, as compared to corn, in biomass production under conditions of diminished soil moisture (Bhat, 2019).

Moreover, the study identified that the least adapted plants under WD conditions were those with taller stature, high chlorophyll concentration, and high shoot FM production. The feasibility of employing morphological and productive traits for selecting WD-tolerant sorghum germplasm is advantageous due to its cost-effectiveness and suitability for implementation in developing countries (Sogoba et al., 2020). In regions where water resources are limited, enhancing water-use efficiency and prioritize more drought-resistant genotypes enhance crop yields with guarantee economic and food security (García-León et al., 2021). Breeding programs for forage sorghum face the challenge of selecting hybrids that yield high biomass per unit area while also featuring larger leaf blade areas to reduce the proportion of fibrous material (Bhat, 2019; Fardin et al., 2023).

The response of the hybrids to WD was distinct from that observed under well-watered conditions, as shown in Figures 3-A and 3-B. Among the hybrids evaluated, AGRI 002-E showed a positive correlation with variables indicating productivity and sustainability (LAI, DM, and WP) in PC1. Under field conditions, this hybrid was considered promising for regions with very clayey-textured soils, with two cuts during cultivation and fertilized and reduced requirement of nitrogen, it produced 96.6 t ha^{-1} of FM and 37.9 t ha^{-1} of DM (Theodoro et al., 2021b). AGRI G1 and BRS 658 were found in the quadrant related to inversely proportional responses to LAI, DM and WP. The other hybrids showed intermediate performance when only 50% of the ETc was replaced through irrigation.

The results obtained in this work shows the morphological variation found among sorghum hybrids, with multiple purpose (Hao et al., 2021), with possible implications for coping with climate changes (Chadalavada et al., 2021).

Plants that produce more shoot biomass, even under WD conditions, are preferable for feed and silage (Bhattarai et al., 2020). However, little is known about whether, under these conditions, there will be significant changes in chemical compositions that may influence animal nutrition (Fardin et al., 2023).

Further research is necessary to fully understand the performance of sorghum crops under water-restricted conditions, including the evaluation of additional hybrids and varying levels of water replacement. As a result, it is prudent to exercise caution when making general recommendations regarding the behavior of the crop in response to abiotic factors, as premature or inaccurate conclusions may lead to frustration and loss of confidence among farmers regarding the potential of sorghum for various food production sectors.

Material and methods

Experimental location

The present study was conducted at the Faculty of Veterinary Medicine and Animal Science (FAMEZ) of the Federal University of Mato Grosso do Sul (UFMS), situated in the municipality of Campo Grande, MS, Brazil. The geographic coordinates of the experimental location are 20°30'37.8" S latitude and 54°37' 12.8" W longitude, and the altitude is 532 m. The experiment was conducted under a greenhouse and the climate of the region is classified as Aw (Kottek et al., 2006).

Climatic data was collected by a portable thermohygrometer, located inside the greenhouse and the average air temperature during the experiment was 29.9 ± 2.9 °C, while the mean relative humidity was 65.4 ± 6.6%.

Experimental design

The experimental design of the study was randomized block, following a 5x2 factorial scheme, with four replications, as follow: five sorghum hybrids (AGRI 002-E, AGRI G1, AGRI G2, BREVANT SS318 and BRS 658) x two levels of water loss replacement, namely 50% and 100% of ETc. The choice of hybrids was based on their relevance to some South American countries and their dual-purpose functionality. AGRI 002-E, BREVANT SS318, and BRS 658 are recommended for grazing or silage, while both AGRI G1 and AGRI G2 are utilized for either grazing or grain production.

Soil preparation

A soil sample was obtained and subjected to chemical and physical analyses, revealing the following properties:: pH: 5.33; OM: 34.55 g kg^{-1}; Ca: 6.05 cmol$_c$ dm^{-3}; Mg: 1.20 cmol$_c$ dm^{-3}; K: 0.22 cmol$_c$ dm^{-3}; P: 1.33 mg dm^{-3}; H+Al: 4.6 cmol$_c$ dm^{-3}; Sand: 260 g kg^{-1}; Silt: 130 g kg^{-1}; Clay: 610 g kg^{-1}; field capacity: 0.3001 g g^{-1}; wilting point: 0.2278 g g^{-1}.

Sorghum was cultivated in pots with eight cubic decimeters soil that was sieved through a 5-mm-mesh, homogenized and fertilized according to the results of soil chemical analysis. During sowing, fertilization was performed using a mixed commercial fertilizer (29% N, 8% S, 2% Mg, and 4% Ca) at a rate of 53.5 mg dm^{-3}; single superphosphate (21% P_2O_5 and 18% Ca) at a rate of 214.3 mg dm^{-3}; and boron (10% B) at a rate of 5 mg dm^{-3}. Following fertilization, all pots were labeled, filled with the same volume and mass of soil, and placed in a protected environment.

On December 29, 2021, eight seeds of each sorghum hybrid were manually sowed at a depth of approximately 1 cm in the soil. On the 13th day after sowing (January 11, 2022), uniform thinning was performed in all pots to maintain one plant per pot and avoid nutrient competition, as suggested by Munamava and Riddoch (2001). Plants with six expanded leaves (V6) were fertilized with 159.09 mg dm^{-3} of urea (44% N) as top-dressing on January 27, 2022. Throughout the sorghum plant's development, pests and diseases were controlled when necessary.

Irrigation

The replenishment of water lost due to evapotranspiration was conducted following the drainage lysimetry principle, which was outlined by Chapuis et al. (2012). An appropriate volume of water was supplied to the soil on a daily basis to attain field capacity. The amount of water evapotranspired by the sorghum crop was calculated by subtracting the volume of drained water collected on the following day.

Seven lysimeters were installed in the protected environment to measure evapotranspiration. These lysimeters were similar pots to those of the experimental plots, placed in eight-liter buckets on PVC pipe supports. Each lysimeter contained one sorghum plant and all the hybrids were sowed at least once. To obtain sorghum evapotranspiration, irrigation and drainage collections were performed daily in the morning.

All the plants in the treated pots were irrigated daily with 100% replacement of ETc until the vegetative stage reached eight expanded leaves (V8), which corresponded to 33 DAE. On 02/04/2022 (33 DAE in the stage V8), both treatments were imposed with water replacement levels of 100% and 50% of ETc. The replacement of 50% of ETc was considered to be capable of inducing WD in the plants.

Evaluations

Morphology and chlorophyll content in leaves

The assessment of morphological characteristics and estimation of chlorophyll content in leaves were carried out every 10 days, in the morning, after the application of the two levels of water replacement treatments in the vegetative stage V8 for all hybrids. The evaluated variables included PH, measured using a measuring tape from the last exposed ligule to the ground; SD, measured using a digital caliper at the height corresponding to half the plant height; LAI; and CHLi, determined according to Zhu et al. (2012).

To comprehend the changes in the chlorophyll content of leaves during the course of the experiment, CHLi was determined using the portable chlorophyll meter atLeaf CHL Plus. The measurements were taken in the middle third of the blade of the most recently expanded leaf, as per the guidelines of Oliveira et al. (2020) and Xavier et al. (2021). Twenty readings were taken per experimental plot (Zhu et al., 2012).

Biomass and dry matter of shoot and root system

Two cuts were executed at the first node above the ground level. The first cut of forage-silage sorghum hybrids (AGRI 002-E, BREVANT SS318, and BRS 658) was performed on April 14, 2022 (96 days after emergence). Grazing-grain purpose hybrids (AGRI G1 and AGRI G2) were cut after complete panicle emergence on April 27, 2022 (117 days after emergence).

The FM, DM and dry matter content (Rezende et al. 2020) of the aerial part of the sorghum plant were determined after cutting. Then, the roots in each pot were extracted to determine the dry matter of the root system for each experimental plot, following the procedure described by Fernandes et al. (2020). To separate the root system from the soil, the contents of the pot were placed on a sieve with a 2 mm mesh, and the roots were washed off the soil using running water.

Area under the progress curve

To assess the impact of certain variables throughout the experiment, such as LAI and CHLi, their areas under the curve (AUPC) were calculated using the methodology proposed by Rosyara et al. (2007).

Statistical analysis

The dataset was subjected to an analysis of variance, and the means were subsequently compared using the Scott-Knott test at a significance level of 5%. In the context of PCA, we utilized the data derived from the most recent assessments following the methodology outlined by Chaves et al. (2023). To ensure that each descriptor had a mean of zero and a variance of one, the dataset was standardized. The statistical analysis was performed using R software version 4.0.

Conclusions

The morphology of sorghum hybrids is affected by water deficit, resulting in reductions in plant height, stem diameter, leaf area index, and chlorophyll content, and causing up to 37% losses in shoot dry mass productivity.

Through PCA analysis, AGRI 002-E, BREVANT SS318, and BRS 658 can be recommended for grazing-silage production without water restriction, while AGRI 002-E performs better under water-deficient conditions.

Silage hybrid with more leaf area and higher water productivity have better performance under water-limited conditions, while those with taller stature, high chlorophyll concentration, and high shoot FM production were found to be less adapted.

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