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Water availability and growing season temperature on the performance of sorghum cultivars

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ABSTRACT: Plant yield is directly affected by the increase in air temperature and the water availability in the soil. Therefore, the objective with this study was to evaluate the physiological and productive performance of sorghum cultivars as a function of soil water availability and temperature at the cultivation time. The research was carried out at Embrapa Semi-Arid, municipality of Petrolina, Pernambuco state, Northeast region, Brazil, with planting in June 2021 and January 2022. The experiment was conducted in a randomized block design with a 2 × 6 × 4 factorial arrangement, with two growing seasons (season 1: planting in June; season 2: planting in January), six sorghum cultivars (AGRI002E, BRS 716, BRS 506, SF 15, IAC Santa Elisa and BRS Ponta Negra) and four water availability levels (25, 50, 75, and 100%), with four replications. The following variables were evaluated: total dry mass, water use efficiency, photosynthesis, stomatal conductance, transpiration and leaf temperature. The SF 15 and BRS Ponta Negra cultivars produced the highest amount of total dry mass when planted in June, with maximum temperatures ranging from 26 to 34 ºC and 100% water availability. The AGRI002E cultivar showed higher dry mass production, photosynthesis, stomatal conductance and leaf transpiration rates among the other cultivars in season 2, with 100% of soil water retention capacity, demonstrating adaptation to the increase in temperature.

Key words: abiotic stress; climate changes; physiology; *Sorghum bicolor* (L.) Moench

Disponibilidade hídrica e temperatura da época de cultivo no desempenho de cultivares de sorgo

RESUMO: O rendimento das plantas é afetado diretamente pelo aumento da temperatura do ar e pela disponibilidade de água no solo. Diante disso, objetivou-se avaliar o desempenho fisiológico e produtivo de cultivares de sorgo em função da disponibilidade de água no solo e da temperatura da época de cultivo. A pesquisa foi realizada na Embrapa Semiárido, localizada no município de Petrolina, Pernambuco, região Nordeste, Brasil, com plantio em junho de 2021 e janeiro de 2022. O experimento foi conduzido com delineamento experimental em blocos casualizados, em arranjo fatorial 2 × 6 × 4, sendo duas épocas de cultivo (Época 1: plantio em junho; Época 2: plantio em janeiro), seis cultivares de sorgo (AGRI002E, BRS 716, BRS 506, SF 15, IAC Santa Elisa e BRS Ponta Negra) e quatro níveis de disponibilidade hídrica (25, 50, 75 e 100 %), com quatro repetições. Foram avaliadas: a massa seca total, a eficiência no uso da água, a fotossíntese, a condutância estomática, a transpiração e a temperatura foliar. As cultivares SF 15 e BRS Ponta Negra produziram maior quantidade de massa seca quando plantadas em junho, com temperaturas máximas variando de 26 a 34 ºC e 100 % de disponibilidade hídrica. A cultivar AGRI002E apresentou maior produção de massa seca, taxa de fotossíntese, condutância estomática e transpiração foliar na época com as temperaturas mais altas, com 100% da capacidade de retenção de água do solo, demonstrando adaptação ao aumento da temperatura.

Palavras-chave: estresse abiótico; mudanças climáticas; fisiologia; *Sorghum bicolor* (L.) Moench

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Introduction

The Brazilian semi-arid region has peculiar environmental and climatic characteristics, along with irregular precipitation ranging from 400 to 800 mm, and dry periods lasting six to eight months (Araújo Filho et al., 2019). Faced with this challenge, studies that provide specific local technologies, such as efficient water use and selecting cultivars which are tolerant to water deficit and high temperatures are important for maintaining agricultural activity in the region (Barros et al., 2023).

In this context, sorghum [*Sorghum bicolor* (L.) Moench.] is a crop alternative because it presents significant tolerance to the stressful conditions of water deficit and high temperatures which are common conditions in semi-arid regions (Chadalavada et al., 2021), and due to its productive potential for multiple uses such as in producing high-quality grains, silage production (Tabosa et al., 2020), and human food (Meena et al., 2022); in addition, it can be used as biomass with potential for burning and for biofuel production (Silva et al., 2018). These characteristics contribute to its placement as the fifth most cultivated cereal in the world (FAO, 2022).

According to Ribas (2003), the ideal temperature for sorghum cultivation depends on the different phenological stages, being between 21-35 °C for germination, 26-34 °C for vegetative growth, and 21-35 °C in the reproduction phase. Furthermore, plants need 330 kg of water to produce one kilogram of dry mass (Magalhães et al., 2010). Thus, the changes predicted by climate scenarios, including increased air temperature and prolonged dry periods (IPCC, 2021) represent a warning to the productive potential of sorghum, since most sorghum producing regions are characterized by high temperatures and low water availability (Eggen et al., 2019; Prasad et al., 2021). Thus, selecting cultivars tolerant to increased air temperature and water deficit is one of the adaptation measures that can contribute to maintaining and/or increasing sorghum production.

Nascimento (2022) evaluated the response of sorghum cultivars under increases of 4.8 and 6.3 °C in air temperature under controlled conditions in order to understand the response of cultivars to future scenarios. This increase positively affected sorghum dry mass production, demonstrating the crop's tolerance to high temperatures. However, abiotic stresses do not occur in isolation in a natural environment, and the impact of water deficit depends on the interaction with air temperature (Jumrani & Bhatia, 2018). This is because the water demand by plants tends to increase under high temperatures, with greater water losses due to evapotranspiration, thereby reducing the water available to plants (Bergamaschi & Bergonci, 2017). Furthermore, sensitivity to stresses depends on the development stage.

Compared to other cereal crops, sorghum is more tolerant to water deficit and therefore can be grown in water-scarce areas (Devnarain et al., 2016). However, the levels of water deficit tolerance vary among its genotypes and the developmental stage of the crop (Magalhães et al., 2021). The genotypes considered more tolerant exhibit higher biomass yield and greater tolerance index under lower soil moisture conditions, along with a high capacity to restore leaf apparatus after water stress (Fracasso et al., 2016).

Obtaining information on these aspects can provide a baseline to further improve tolerance to abiotic stress in sorghum, especially in cultivars used in arid and semi-arid regions. Thus, the present work aimed to evaluate the dry mass weight and physiological performance of sorghum cultivars under different water availability levels in two planting times.

Materials and Methods

The experiment was conducted at Embrapa Semi-Arid, municipality of Petrolina, Pernambuco state, Northeast region, Brazil (9° 8' 8.9" S, 40° 18' 33.6" W), between June 2021 and April 2022. The climate data obtained are shown in Figure 1.

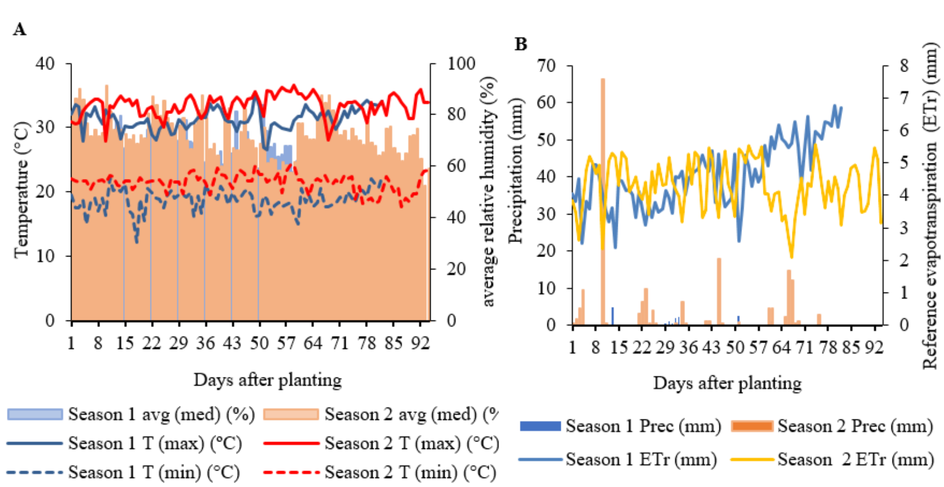

Figure 1. (A) Maximum temperature [T max (°C)], minimum temperature [T min (°C)], average relative humidity [avg Rh (%)]; (B) precipitation [Prec (mm)], and reference evapotranspiration [ETr (mm)] in two sorghum planting seasons.

The maximum temperature varied between 26.6 and 34.2 °C in the first growing season, and between 27.9 and 36.6 °C in the second growing season, with an average difference of 2.1 °C between seasons, and precipitation was 15.6 and 176.7 mm at stations 1 and 2, respectively. The experiment was conducted in randomized blocks with a 2 × 6 × 4 factorial arrangement and two growing seasons (season 1: planting in June and season 2: planting in January), six sorghum cultivars with potential for biomass (AGRI002E, BRS 716, BRS 506, SF 15, IAC Santa Elisa and BRS Ponta Negra) and four soil water availability levels - WA (25, 50, 75, and 100% of the maximum soil water retention capacity - WRC), with four repetitions.

The cultivars were planted in 26 L pots 30 cm apart and placed in the open air. The soil used was classified as red yellow plintic eutrophic Argisol. Physical characteristics of 83.1% sand, 11.9% silt, and 4.9% clay. The foundation fertilization was carried out three days before planting, according to the results of the chemical analysis of the soil (Table 1) and the recommendations for the crop.

A total of 10 seeds were planted per pot in holes five centimeters deep, thinning after 15 days, keeping only one plant per pot. Irrigation was calculated based on the maximum soil water retention capacity (WRC), and irrigation management was carried out by TDR (Time Domain Reflectometry) using Campbell's TDR100 model. Coaxial cable probes with three rods and TDR calibration were used according to Batista et al. (2016). Irrigations were carried out every two days in line with the soil water balance according to previously defined treatments.

Harvesting was performed when the plants reached the beginning of growth stage three of the sorghum plant (GS3), characterized by grain ripening and greater lignification of plant tissues. The amount of accumulated biomass is greatest in this phase. The plants were cut close to the ground, placed in paper bags, identified and sent to dry in a forced aeration oven at a temperature of 60 °C until reaching a constant weight. After drying, the plant material was weighed on a digital scale to obtain the total dry mass weight (g). Next, the water use efficiency (WUE) (g L^{-1}) was calculated through the ratio of the total dry mass (g) with the amount of water used in irrigation during the entire cycle.

Physiological evaluations were carried out 60 days after planting between 8 am and 10 am, selecting completely expanded leaves from each plant considering uniform characteristics in terms of color, maturity and size. Gas exchanges was determined using the Portable Infrared Gas Analyzer (IRGA) model Li 6400 XT (LI-COR), under photosynthetically active radiation maintained at 1.700 μmol m^{-2} s^{-1}. The evaluated variables were: photosynthesis (*A*), stomatal conductance (gs), transpiration rate (E) and leaf surface temperature (LsT).

The data obtained were subjected to analysis of variance (ANOVA) and the mean by the Scott Knott test at 5% significance for interaction between seasons and cultivars using the SISVAR 5.6 program (Ferreira, 2011). A regression analysis was performed in the presence of significance to assess the influence of water availability.

Results

For all the parameters evaluated: photosynthesis (*A*), stomatal conductance (gs), transpiration (E), leaf temperature (LsT), dry mass weight (DMW) and water use efficiency (WUE), the analysis of variance showed significant values for the interaction season x cultivar x water availability (Table 2).

The rates of increase in the cultivars dry matter weight, within the range of 25 to 100% DH, varied from 714 to 1,444% during season 1 for the IAC Santa Elisa and Agri002E

Table 1. Chemical characterization of the soil.

ECse	pH	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	$H^+ + Al^{3+}$	SB	CEC	V
(dS m^{-1})		(mg dm^{-3})	(cmol$_c$ dm^{-3})								(%)
2.46	5.18	42.5	0.45	0.07	2.78	1.69	0.00	0.84	4.99	5.7	85.56

ECse - Electrical conductivity of saturation extract; P - Available phosphorus extracted by Mehlich; Ca - Exchangeable calcium; Mg - Exchangeable magnesium; Na - Exchangeable sodium; K - Exchangeable potassium; Al - Exchangeable acidity; SB - Sum of bases; CEC - Cation exchange capacity at pH 7.0; V - Base saturation.

Table 2. Summary of the analysis of variance, by mean square, for dry mass weight (DMW), water use efficiency (WUE), photosynthesis (*A*), stomatal conductance (gs), transpiration (E) and leaf temperature (LsT) of: Agri002E, BRS 506, BRS 716, SF 15, IAC Santa Elisa, and BRS Ponta Negra sorghum cultivars, depending on water availability, with planting in June and January.

Variation source	DF	Mean square					
		DMW	WUE	*A*	gs	E	LsT
Season (S)	5	10,735.44*	8.54*	111.99*	0.01*	0.21*	345.35*
Cultivars (cv)	5	19,407.17*	3.29*	417.25*	0.01*	5.56*	19.14*
Water availability (WA)	3	669,383.65*	19.77*	4,880.62*	0.12*	70.08*	182.83*
S × cv	25	23,676.41*	3.75*	267.61*	0.00*	6.14*	5.95*
S × WA	15	19,003.46*	3.10*	331.44*	0.00*	8.96*	15.09*
cv × WA	15	6,620.6372*	0.79*	121.65*	0.00*	1.79*	8.24*
S × cv × WA	75	5,501.38*	0.86*	141.93*	0.00*	2.47*	5.11*
Residue	144	204.65	0.04	1.32	0.00	0.02	0.13
CV%		8.35	8.31	4.59	4.45	4.57	1.13

DF - Degree of freedom; CV - Coefficient of variation; * Significant at 5% of probability according to Scott-Knott test.

varieties, respectively, and from 293 to 837% for the BRS 506 and Agri002E varieties, respectively, during season 2.

The Agri002E cultivar presented the highest total dry mass among the other cultivars planted in January, with an increase of 30% in the total dry mass weight when irrigated without water restriction, with 100% water availability (WA) compared to the planting carried out in June, producing about 374.60 g per plant (Table 3). The SF 15 and BRS Ponta Negra cultivars showed the highest total dry mass in cultivation in the season with the lowest temperatures (season 1) and 100% WA. These cultivars showed a reduction of 34 and 37% in their total dry mass when planted in January, respectively, compared to when planted in the other period (Table 3).

Among the analyzed cultivars, the BRS 506 cultivar stood out for water use efficiency (WUE) with 83 and 90%, in seasons 1 and 2, respectively. The other cultivars had higher WUE with 100% WA. The SF 15 and BRS Ponta Negra cultivars obtained the highest WUE when planted in June, with a reduction of approximately 22 and 23%, respectively, compared to the planting carried out in January. On the other hand, the AGRI002E and IAC Santa Elisa cultivars had the highest WUE when planted in January, with 4.45 and 2.99 g L^{-1} of dry mass at 100% water availability (WA), with 66 and 37% higher WUE, respectively, than the planting carried out in June (Table 3). The BRS 716 cultivar did not show a significant difference between growing seasons for WUE under 100% WA, with an average of 3.28 g L^{-1} (Table 3).

The interaction of cultivars × planting time × WA affected photosynthesis (*A*), stomatal conductance (gs), leaf transpiration (E) and leaf surface temperature (LsT). The sorghum cultivars showed variability in terms of physiological responses in the two growing seasons under both water stress conditions and at the maximum water availability capacity. Furthermore, regardless of planting time, the sorghum cultivars showed a reduction in physiological activity due to water restriction (Tables 4 and 5).

Under higher WA conditions (100%) and during cultivation with planting in June, the AGRI002E cultivar

Table 3. Total dry mass (TDM) and water use efficiency (WUE) of: Agri002E, BRS 506, BRS 716, SF 15, IAC Santa Elisa, and BRS Ponta Negra sorghum cultivars, depending on water availability, with planting in June and January.

Planting season	Cultivar	TDM (g)					WUE (g L^{-1})				
		Water availability (%)				R^2	Water availability (%)				R^2
		25	50	75	100		25	50	75	100	
June (Season 1)	Agri002E	23.98 aA	83.23 dB	168.88 dB	286.59 cB	1	0.93 bB	1.59 dB	2.12 dB	2.68 dB	0.99
	BRS 506	30.87 aA	126.60 bA	272.19 bA	305.66 cA	0.97	1.21 bB	2.49 bA	3.57 aA	3.03 cA	0.96
	BRS 716	33.28 aB	118.19 bA	199.59 cB	346.98 bA	0.99	1.29 bB	2.32 bA	2.43 cB	3.25 cA	0.92
	SF 15	29.72 aA	104.70 cA	315.52 aA	458.92 aA	0.98	1.21 bB	2.09 cA	3.86 aA	4.37 aA	0.95
	IAC Santa Elisa	27.99 aA	84.84 dB	158.44 dA	228.07 dB	0.99	1.10 bB	1.72 dB	1.97 dB	2.18 eB	0.92
	BRS Ponta Negra	39.95 aB	144.05 aA	260.88 bA	442.62 aA	0.99	1.57 aB	2.86 aA	3.25 bA	4.05bA	0.97
January (Season 2)	Agri002E	39.58 bA	161.84 aA	259.06 aA	374.60 aA	0.99	1.88 dA	3.46 aA	3.74 aA	4.45 aA	0.95
	BRS 506	41.50 bA	111.99 bA	149.20 dB	163.17 dB	0.99	2.06 cA	2.50 cA	2.37 cB	2.08 dB	0.94
	BRS 716	66.72 aA	113.15 bA	228.65 bA	297.80 bB	0.97	2.93 aA	2.42 cA	3.24 bA	3.31 bA	0.55
	SF 15	48.87 bA	101.22 bA	199.18 cB	301.10 bB	0.99	2.38 bA	2.23 cA	2.98 bB	3.39 bB	0.91
	IAC Santa Elisa	30.85 bA	123.73 bA	168.77 dA	258.55 cA	0.98	1.53 eA	2.69 cA	2.40 cA	2.99 cA	0.77
	BRS Ponta Negra	64.70 aA	143.89 aA	205.94 cB	278.77 cB	0.99	3.07 aA	3 bA	3.04 bA	3.12 cB	----

Means followed by the same lowercase letter in the column for the same growing season, and capital letter in the column between the growing seasons for the same cultivar, do not differ from each other by the Scott-Knott test at 5% probability.

Table 4. Photosynthesis (µmol CO_2 m^{-2} s^{-1}) and stomatal conductance (mol H_2O m^{-2} s^{-1}) of: Agri002E, BRS 506, BRS 716, SF 15, IAC Santa Elisa, and BRS Ponta Negra sorghum cultivars depending on water availability, with planting in June and January.

Planting season	Cultivar	Photosynthesis (µmol de CO_2 m^{-2} s^{-1})					Stomatal conductance (mol H_2O m^{-2} s^{-1})				
		Water availability (%)				R^2	Water availability (%)				R^2
		25	50	75	100		25	50	75	100	
June (Season 1)	Agri002E	7.41 dB	31.08 aA	38.06 aA	52.55 aA	0.97	0.04 eB	0.14 aA	0.18 aA	0.24 aA	0.97
	BRS 506	8.14 dB	17.01 dA	20.13 cA	28.58 eA	0.97	0.04 eB	0.07 eA	0.09 cA	0.13 eA	0.98
	BRS 716	18.64 aA	30.99 aA	37.47 aA	31.77 dB	0.98	0.08 bA	0.14 aA	0.17 aA	0.15 dA	0.99
	SF 15	11.58 cB	20.43 cA	20.79 cB	35.00 cB	0.91	0.06 dB	0.08 dA	0.09 cB	0.16 cB	0.94
	IAC Santa Elisa	15.17 bB	24.43 bA	29.93 bB	41.27 bB	0.98	0.07 cA	0.12 bA	0.14 bB	0.19 bB	0.99
	BRS Ponta Negra	17.07 aA	24.35 bA	29.01 bA	29.93 eB	0.99	0.09 aA	0.11 cA	0.14 bA	0.15 dB	0.96
January (Season 2)	Agri002E	19.36 aA	17.87 bB	21.03 dB	37.57 dB	0.98	0.06 bA	0.06 cB	0.11 cB	0.17 bB	0.99
	BRS 506	15.36 bA	16.44 bA	19.50 eA	21.82 fB	0.97	0.05 cA	0.06 cB	0.06 dB	0.11 dB	0.94
	BRS 716	11.98 cB	16.77 bB	21.33 dB	34.03 eA	0.98	0.04 cB	0.06 cB	0.11 cB	0.15 cA	0.98
	SF 15	14.74 bA	16.92 bB	27.79 bA	51.66 aA	0.99	0.07 aA	0.06 cB	0.12 bA	0.23 aA	0.99
	IAC Santa Elisa	18.27 aA	13.69 cB	36.59 aA	47.42 bA	0.89	0.06 bA	0.07 bB	0.16 aA	0.23 aA	0.98
	BRS Ponta Negra	14.27 bB	21.59 aB	22.88 cB	45.26 cA	0.93	0.05 cB	0.10 aB	0.10 cB	0.23 aA	0.92

Means followed by the same lowercase letter in the column for the same growing season, and capital letter in the column between the growing seasons for the same cultivar do not differ from each other by the Scott-Knott test at 5% probability.

Table 5. Transpiration (mmol H_2O m^{-2} s^{-1}) and leaf temperature (°C) of: Agri002E, BRS 506, BRS 716, SF 15, IAC Santa Elisa, and BRS Ponta Negra sorghum cultivars depending on water availability, with planting in June and January.

Planting season	Cultivar	Transpiration (mmol H_2O m^{-2} s^{-1})					Leaf temperature (°C)				
		Water availability (%)				R^2	Water availability (%)				R^2
		25	50	75	100		25	50	75	100	
June (Season 1)	Agri002E	1.34 cB	4.05 aA	6.07 aA	8.06 aA	0.99	33.36 bB	32.81 aB	31.11 bB	30.49 aB	0.95
	BRS 506	1.26 cB	1.91 dB	3.29 cA	4.58 cA	0.99	33.67 bB	32.46 bB	31.68 aB	30.46 aB	0.99
	BRS 716	2.59 aA	3.80 bA	3.21 cA	4.76 cA	0.69	32.88 cB	32.27 cB	31.25 bA	29.97 aB	0.97
	SF 15	1.29 cB	2.33 dB	2.82 dB	4.28 dB	0.97	32.66 cB	31.81 cA	31.01 bB	30.85 aB	0.93
	IAC Santa Elisa	0.51 dB	2.96 cA	4.30 bA	5.78 bA	0.99	33.07 cB	32.43 bA	30.24 cB	26.61 bB	1.00
	BRS Ponta Negra	2.10 bB	3.09 cA	3.35 cA	4.42 dB	0.95	34.67aB	32.95 aA	32.04 aA	30.35 aB	0.98
January (Season 2)	Agri002E	2.58 cA	2.78 bB	2.98 cB	4.92 bB	0.95	38.69 aA	37.22 bA	32.94 aA	32.65 aA	0.91
	BRS 506	2.68 bA	2.76 bA	3.22 bA	3.13 eB	0.76	37.98 bA	38.53 aA	33.31 aA	33.19 aA	0.76
	BRS 716	2.39 cA	3.05 aB	3.39 aA	3.88 dB	0.98	38.10 bA	36.48 cA	30.78 cA	32.57 aA	0.80
	SF 15	2.47 cA	2.87 bA	3.47 aA	5.67 aA	0.98	34.14 dA	32.00 eA	33.31aA	32.80 aA	0.42
	IAC Santa Elisa	3.36 aA	2.17 cB	3.29 aB	4.25 cB	0.86	37.34 cA	32.79 dA	33.09 aA	30.06 bA	0.87
	BRS Ponta Negra	2.81 bA	3.06 aA	3.49 aA	5.85 aA	0.97	38.96 aA	33.18 dA	32.36 bA	32.98 aA	0.97

Means followed by the same lowercase letter in the column for the same growing season, and capital letter in the column between the growing seasons for the same cultivar do not differ from each other by the Scott-Knott test at 5% probability.

showed the highest photosynthesis, stomatal conductance and leaf transpiration rates compared to the other cultivars. With planting in January, the BRS 506 cultivar showed the lowest values for the same variables (Tables 4 and 5).

The BRS 716, SF 15, Santa Elisa, and Ponta Negra sorghum cultivars under water availability at 100%, showed greater photosynthetic activity when planted in January (season 2) (Table 4), with the SF 15 cultivar standing out among the others at this time with an increase of 48% in photosynthesis. This increase in the photosynthetic rate is related to the increase in stomatal conductance (gs) of this cultivar, which also provided greater transpiration (E) and consequently a decrease in leaf surface temperature (LsT) (Tables 4 and 5). Similar behavioral responses were observed in the BRS Ponta Negra cultivar (Tables 4 and 5).

Under water availability of 100%, the two planting times did not interfere with the stomatal conductance (gs) of the BRS 716 cultivar (0.15 mol H_2O m^{-2} s^{-1}). However, the highest conductance value (0.17 mol H_2O m^{-2} s^{-1}) of this cultivar under WA of 75% was observed for planting in June. The highest stomatal conductance (gs) for planting in January was observed for the SF 15, IAC Santa Elisa, and BRS Ponta Negra cultivars, which did not differ from each other and presented a value of 0.23 mol H_2O m^{-2} s^{-1} in WA of 100% (Table 4).

The planting carried out in January provided a higher leaf transpiration rate (E) for the SF 15 and Ponta Negra cultivars, with an increase of 32% when compared to the planting carried out in June, under 100% WA (Table 5).

The sorghum cultivars increased the leaf temperature under greater water restriction conditions (25% WA) in the two planting periods (Table 5). Planting time 2 (January) generally provided the highest LsT for all cultivars. The BRS Ponta Negra cultivar obtained the highest LsT in the lowest water availability (25% of WA) compared to the other cultivars of 34.67 °C with planting carried out in June. Similar results were also observed during season 2 (January); however, the cultivar showed an increase of 4.29 °C in LsT with WA of 25%.

The IAC Santa Elisa cultivar had the lowest LsT among the cultivars in both planting seasons, with 26.61 °C when planted in June, with at 100% WA. However, when planted in January, the cultivar obtained an increase of 3.45 °C in LsT at 100% of WA (Table 5). The leaf temperature of all cultivars decreased as a function of the increase in WA, regardless of the growing season (Table 5).

Discussion

The sorghum cultivars showed different responses to the growing season and water deficit, and the selection of tolerant cultivars under abiotic stresses is highlighted as an important adaptation measure for maintaining production (Nascimento, 2022; Barros et al., 2023).

The SF 15 and BRS Ponta Negra cultivars in this study obtained a better dry mass weight in the cycle with maximum temperatures between 26.6 and 34.2 °C, and can be recommended for planting in times with mild temperatures. According to Chadalavada et al. (2021), growth and yields can be affected by temperatures above 35 °C. However, the AGRI002E cultivar stood out with adaptation to the increase in temperature, being an alternative for cultivation when faced with an increase of 2.1 °C in temperature. This same cultivar showed higher dry mass production in a study under controlled conditions in response to an increase of 4.8 ºC in temperature, compared to the average temperature seen in season 1 (Nascimento, 2022).

An increase in air temperature of 2.1 °C can reduce sorghum yield through direct impacts on plant metabolism (Magalhães et al., 2014). The negative effect of the increase in temperature on the development of the SF 15 and BRS Ponta Negra cultivars may be related to inhibiting the activity of the enzyme responsible for carbon fixation (rubisco), which reduces the photosynthetic efficiency, increases the respiratory and transpiration rates of the plants, leading to excessive water loss. This in turn leads to an increase in the demand for energy needed for growth and development, with a consequent decrease in biomass production (Santos et al., 2022; Zhang et al., 2022).

On the other hand, plants have thermal needs for their development, and like other plant species, sorghum also has an optimal temperature range for its growth and development. Sorghum is a plant that adapts well to different climatic conditions, but its optimum temperature range for growth is around 25-30 °C. The highest dry mass weight of the AGRI002E cultivar at the time with the highest temperatures confirms its ability to adapt to the high temperature environment, which may be related to greater photosynthetic efficiency. Temperature influences several plant physiological processes, including the photosynthesis, transpiration, and respiration rates, which in turn affect sorghum growth and development (Qaseem et al., 2019). According to the authors, the ideal temperature helps to increase both the metabolic activity and the synthesis of chlorophyll in the plant. In turn, chlorophyll is responsible for absorbing light and producing energy for the plant.

However, excessively high or low temperatures can harm sorghum growth. Very high temperatures can lead to dehydration and protein denaturation, causing damage to leaves and roots, while very low temperatures can slow down growth and affect seed germination (Chadalavada et al., 2021).

The variation in dry mass weight obtained in the different water availability levels for both growing seasons, and the greater production observed for the greater WA (100%) characterize irrigation as a fundamental alternative to increase sorghum productivity. However, in addition to the characteristics related to productivity, water use efficiency will need to be taken into account, since WUE determination aims at financial savings and the rational use of water resources, preventing water loss and other environmental damage factors such as nutrient leaching and increased soil compaction (Kirchner et al., 2019). The WUE obtained by the AGRI002E cultivar at the time with the highest temperatures in WA of 50 and 75% appears as an alternative for cultivation in environments with water limitations. The WUE of the SF 15 cultivar with 75% WA also appears as an alternative when faced with water restrictions in times of lower temperatures (Table 3).

Under water stress conditions, sorghum has physiological properties which allow it to stop growth or reduce its metabolism. Some of the strategies used by the plant to adapt to conditions of water limitation are closing of stomata, accumulating soluble sugars, accumulating proline and developing deep root systems (Tingting et al., 2010). Thus, a reduction in stomatal conductance in the AGRI002E cultivar in season 2 (Table 4) can be seen as a way of adapting the cultivar to water stress and increased temperature. In turn, monitoring gas exchange responses helps to understand the strategies that plants use in managing water and nutrients, since these factors directly affect the physiological processes of the plant (Lima, 2018).

According to Santos et al. (2022), the lack of water results in a reduction in the photosynthetic rate with stomata closure and a substantial loss in productivity. The results obtained in the present study (Tables 4 and 5) confirm the role of water stress in similarly affecting function as plant water status decreases. Thus, the stress caused by water deficiency increases photorespiration and internal oxygen concentration, which in turn results in forming reactive oxygen species (ROS) that lead to cell death, thus reducing total dry matter production (Perry et al., 1983; Terbea et al., 1995).

According to Zhang et al. (2022), plant responses to these stress conditions can determine the crops ability to tolerate and adapt to the limitations imposed by the environment. Taiz et al. (2017) state that plant productivity is limited by the water availability in the environment and the efficiency that the plant has in its use. Therefore, a plant with greater water availability or that is more efficient in its use will have greater adaptation and production.

Water stress significantly affected gas exchange (Tables 4 and 5), as seen in the photosynthesis of AGRI002E and BRS 506 cultivars in season 1, which showed 7.41 and 8.14 μmol of CO_2 m^{-2} s^{-1}, respectively, in the smallest WA (25%). This decrease is due to the assimilation of carbon dioxide (Reichgelt & Andrea, 2019) through the reduced stomatal conductance, by which the AGRI002E and BRS 506 cultivars showed a decrease of 83.3 and 69.2%, respectively, in the conductance at the lowest WA (25%) when compared with WA at 100% (Table 3). This occurred because the need to regulate water loss leads to a decrease in photosynthesis. This reduction usually occurs in the most stressful water conditions during which photosynthetic metabolism is weakened, thereby limiting CO_2 assimilation and affecting crop development and productivity (Taiz et al., 2017; Santos et al., 2022).

Continuous exposure to water deficit also acts on leaf transpiration. As the water available in the soil decreases, transpiration is reduced, preventing water loss and thus maintaining the osmotic adjustment (Taiz et al., 2017). However, with reduced transpiration, there is an increase in the temperature of the leaves in order to maintain adequate water levels inside (Vieira Junior, 2007). Similar results were observed in the present study (Table 5). It is possible that this response is the result of a change in the structure of the enzymes involved in the carboxylation process caused by the increase in leaf temperature, leading to an increase in the fluidity of the chloroplast membranes and a decrease in gas exchange, directly affecting photosynthesis (Chaves et al., 2016).

When grown under abiotic stresses, plants are affected by physiological damage that impairs their growth and development (Raza et al., 2019). In view of this, advances in research need to include studies that evaluate the adaptation mechanisms of plants to adverse environments, such as the evaluation of responses at the cellular and molecular level (gene expression, osmoprotectors and biochemical processes), which act on the capacity of crop tolerance to abiotic stresses (Pandey et al., 2016; Suzuki et al., 2016; Ahmad et al., 2020). Climatic scenarios reinforce the need to select cultivars that are tolerant to abiotic stresses. Thus, research to increase/maintain sorghum production will need to advance with validation tests of selected materials.

Conclusion

Sorghum cultivars showed different dry mass weight and physiological responses depending on water availability and planting time.

Water restriction negatively affects the physiological responses of sorghum plants, which reduced plant development and consequently the final yield.

The SF 15 and BRS Ponta Negra cultivars present higher dry matter production in seasons with temperatures between 26.6 and 34.2 °C.

The productive performance of the AGRI002E cultivar was higher with planting at the time when the temperature increased by 2.1 °C.

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Compliance with Ethical Standards

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