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CRESCIMENTO E DESENVOLVIMENTO DA CULTURA DO SORGO SOB DÉFICIT HÍDRICO

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1 RESUMO

A análise de crescimento é uma importante ferramenta que produz conhecimentos de valor prático e informações exatas referentes ao crescimento e comportamento das culturas. Objetivou-se neste estudo avaliar o crescimento e desenvolvimento de plantas de sorgo (*Sorghum bicolor* L. Moench.) submetidas a déficit hídrico. O experimento foi conduzido em casa de vegetação climatizada no Instituto Federal Goiano – Campus Rio Verde, GO. O delineamento experimental utilizado foi o de blocos ao acaso, analisado em esquema de parcela subdividida 4 × 8, com quatro repetições. Os tratamentos foram compostos pela combinação de quatro reposições hídricas (25, 50 e 75 e 100%), e oito épocas de coleta (10, 17, 24, 31, 38, 45, 52 e 59 dias após a emergência). Para a semeadura foi utilizado o cultivar de sorgo granífero Buster que possui como principais características a precocidade, sanidade e rendimento. As variáveis avaliadas foram altura de planta, diâmetro de colmo, número de folhas, número entrenós, comprimento de entrenós, comprimento de raiz, volume de raiz, área foliar, área foliar específica, razão de peso foliar e razão de área foliar. O volume de raiz do sorgo irrigado a cada sete dias após a emergência, apresenta um acréscimo médio de aproximadamente 13,90%.

Palavras-Chave: *Sorghum bicolor*, biometria, manejo de irrigação, reposição hídrica.

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GROWTH AND DEVELOPMENT OF SORGHUM CROPS UNDER WATER DEFICIT

2 ABSTRACT

Growth analysis is an important tool that provides practical value and accurate information regarding crop growth and behavior. The objective of this study was to evaluate the growth and development of sorghum plants (*Sorghum bicolor* L. Moench). subjected to water deficit. The experiment was conducted in a climate-controlled greenhouse at the Instituto Federal Goiano – Campus Rio Verde, GO. The experimental design used was randomized blocks, analyzed in a

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4 × 8 split-plot scheme, with four replicates. The treatments consisted of combinations of four water replacements (25, 50, 75 and 100%) and eight collection times (10, 17, 24, 31, 38, 45, 52 and 59 days after emergence). The grain sorghum cultivar Buster was used for sowing, which has the main characteristics of precocity, health and yield. The variables included plant height, stem diameter, number of leaves, number of internodes, internode length, root length, root volume, leaf area, specific leaf area, leaf weight ratio and leaf area ratio. The root volume of sorghum irrigated every seven days after emergence showed an average increase of approximately 13.90%.

Keywords: *Sorghum bicolor*, biometrics, irrigation management, water replacement.

3 INTRODUCTION

Sorghum is a C4 plant with short days and high photosynthetic rates. Notably, sorghum has three growth stages: the first growth phase, growth stage 1 (EC1), extends from planting to panicle initiation; the next phase (EC2) comprises panicle initiation until flowering; and the third growth phase (EC3) extends from flowering to physiological maturation (Magalhães; Durães, 2003; Palacios-Diaz *et al.*, 2023).

The sorghum plant adapts to a range of planting environments, even under water deficit conditions, as it has physiological characteristics that allow it to halt its growth or decrease its metabolic activities during water stress and restart it when water becomes available (Masojidek *et al.*, 1991; Dourado *et al.*, 2022). This characteristic allows crops to be able to develop and expand in growing regions with irregular rainfall distributions and in succession to summer crops (Rodrigues, 2010; Rakgotho *et al.*, 2022). Sorghum responds to environmental changes, mainly temperature and day length; therefore, as it originates from hot regions, it is greatly harmed by low temperatures, which delay the crop cycle (Silva *et al.*, 2013; Bazaluk; Havrysh; Nitsenko, 2021).

Water stress influences all phases of sorghum cultivation, from germination, when it is possible to distinguish seeds with better physiological quality, to the final stages of grain filling (Oliveira; Gomes Fiho, 2009; Mendoza-Grimón *et al.*, 2021). However, the phase in which water stress causes the greatest loss of grain productivity is the reproductive phase. With stress in this phase, several potential seeds fail to form, either because of abortion or insufficient panicle development, and even after ovule fertilization, water stress compromises grain filling (Lima *et al.*, 2011; Nikolaou *et al.*, 2020).

When water deficit in sorghum occurs at stage EC1, it causes less damage to the plant than at EC2, since at stage EC2, water scarcity results in a reduction in panicle and leaf growth rates and in the number of seeds per panicle. These effects are likely due to a reduction in leaf area, increased stomatal resistance, decreased photosynthesis and disorganization of the hormonal state of the differentiating panicle. When water shortage occurs at EC3, rapid senescence of the lower leaves occurs, with a consequent reduction in grain yield (Magalhães *et al.*, 2012; Mendoza-Grimón *et al.*, 2021; Dourado *et al.*, 2022).

Growth analysis is an important tool that provides practical value and accurate information regarding plant growth and behavior, is expressed in the morphophysiological conditions of plants and quantifies net production, which is derived from the photosynthetic process, is the result of the performance of the assimilatory system during a certain period of time and allows the identification of the productive capacity of different varieties and the investigation of the effects of crop management (Benincasa, 2003; Oliveira *et al.*, 2010; Palacios-Diaz *et al.*, 2023).

The aim of this study was to evaluate the growth and development of sorghum plants (*Sorghum bicolor* L. Moench). subjected to water deficit.

4 MATERIALS AND METHODS

The experiment was carried out in a greenhouse installed in the experimental area of IFGoiano – Campus Rio Verde. The greenhouse is made up of a 150-micron transparent polyethylene plastic film covering and closed sides, with a shade cloth with 30% interception. The geographic coordinates of the installation site are 17°48'28" S and 50°53'57" W, with an average altitude of 720 m. The climate of the region is classified according to Köppen and Geiger (1928) as Aw (tropical), with rain from October to May and drying from June to September. The average annual temperature varies from 20 to 35°C.

Pots containing 8 kg of soil prepared from a mixture of two parts of typical dystroferric Red Latosol soil collected in an area with no history of herbicide use that could compromise sorghum cultivation and one part sand were used. The physical and chemical characteristics of the soil are described in Table 1.

Table 1. Physicochemical characteristics of the soil used in the pots

Density	**Porosity Total**	**Sand**	**Silt**	**Clay**	**Sorptive Complex** Ca $^{+2}$	Mg $^{+2}$	In $^{+}$	K $^{+}$	**N**	**pH** $_{ps}$
g cm $^{-3}$	%	g kg $^{-1}$			cmolc kg $^{-1}$				%	-
1.21	53.03	46.3	17.4	32.2	3.55	3.26	0.13	0.58	0.19	5.72

$^{Ca2+}$ and $^{Mg2+ were}$ extracted with 1 mol/L KCl at pH 7.0; Na+ and $^{K+ were}$ extracted with 1 mol/L $^{NH4OAc\ at}$ pH 7.0.

The experimental design used was randomized blocks, analyzed in a 4 × 8 split-plot scheme, with four replicates. The treatments consisted of four water replacements (25, 50, 75 and 100%) and eight evaluation times (10, 17, 24, 31, 38, 45, 52 and 59 days after emergence). The grain sorghum cultivar Buster was used for sowing, which has the main characteristics of recocity, health and yield.

The plants were sown directly into pots, where four seeds were deposited. Immediately after emergence, thinning was performed to obtain a final population of two plants per pot. Fertilization was carried out as recommended by Novais, Neves and Barros (1991) by dilution with 0.86 and 0.58 g kg $^{-1}$ MAP and KCl, respectively, and urea was divided into two applications at 20 and 40 days after emergence, with each application in the experiment being 0.9 g pot $^{-1}$.

To obtain the recommended irrigation, three drain vessels (drainage lysimeters) were used for each water replacement (RH), which were considered 100% deep. A depth of water was added to these drains until the vessels began to drain.

The percolated water found in the collectors was measured in a test tube with a known volume (500 mL) with an accuracy of 0.5 mL, and the value was subtracted from the initial amount irrigated. This procedure was performed for the nine drainage lysimeters, where their averages were then obtained. The amount retained in the vessel was considered the recommendation, and these values were used to obtain the other irrigation percentages (25, 50 and 75%). A drip irrigation system was installed in the greenhouse with registers, which were used to control the water that was inserted into each vessel, with one register for each treatment and its due repetitions. The drip tube was placed on the surface of the vessels, where each vessel received water from an emitter. Before the water reached the drip tubes, it was passed through a glycerin pressure gauge to measure the pressure.

Eight collections were carried out at seven-day intervals to quantify the growth of the sorghum plants. The variables evaluated were plant height, stem diameter, number of leaves, number of internodes, internode length, root length, root volume, leaf area, specific leaf area, leaf weight ratio and leaf area ratio.

Plant height was assessed on the basis of the length of the main stem from the stem to the last node (plant apex), and the stem diameter was measured at the height of the plant stem with a digital caliper. The number of internodes that accumulated on the main stem, as well as the number of leaves emitted, was determined. The leaf area was determined by obtaining a digital image of the leaf and integrating and calculating the leaf area via QUANT V.1.0.1 software (Vale; Fernandes Filho; Liberato, 2001).

The roots were washed in running water to remove all soil residues, and the root volume was measured by displacing a column of water in a graduated cylinder. The lengths of the largest root and internodes were measured via a tape measure and ruler, respectively.

The plant drying procedure to obtain dry mass consisted of placing each plant in properly numbered paper bags according to each treatment and placing it in a drying oven with air circulation and renewal for 48 h at 65 °C (Lacerda; Freitas; Silva, 2009). All weights used to obtain dry mass were performed on a scale with an accuracy of 0.01 g. The total dry matter of the plant was obtained by the sum of the dry matter masses of the roots, stems and leaves. The specific leaf area (SLA), leaf weight ratio (LWR) and leaf area ratio (LAR) were obtained via equations (1) to (3), according to Marafon (2012).

$$AFE = AF/MSf \quad (1)$$

$$RPF = MSt/MSf \quad (2)$$

$$RAF = AFE \times RPF \quad (3)$$

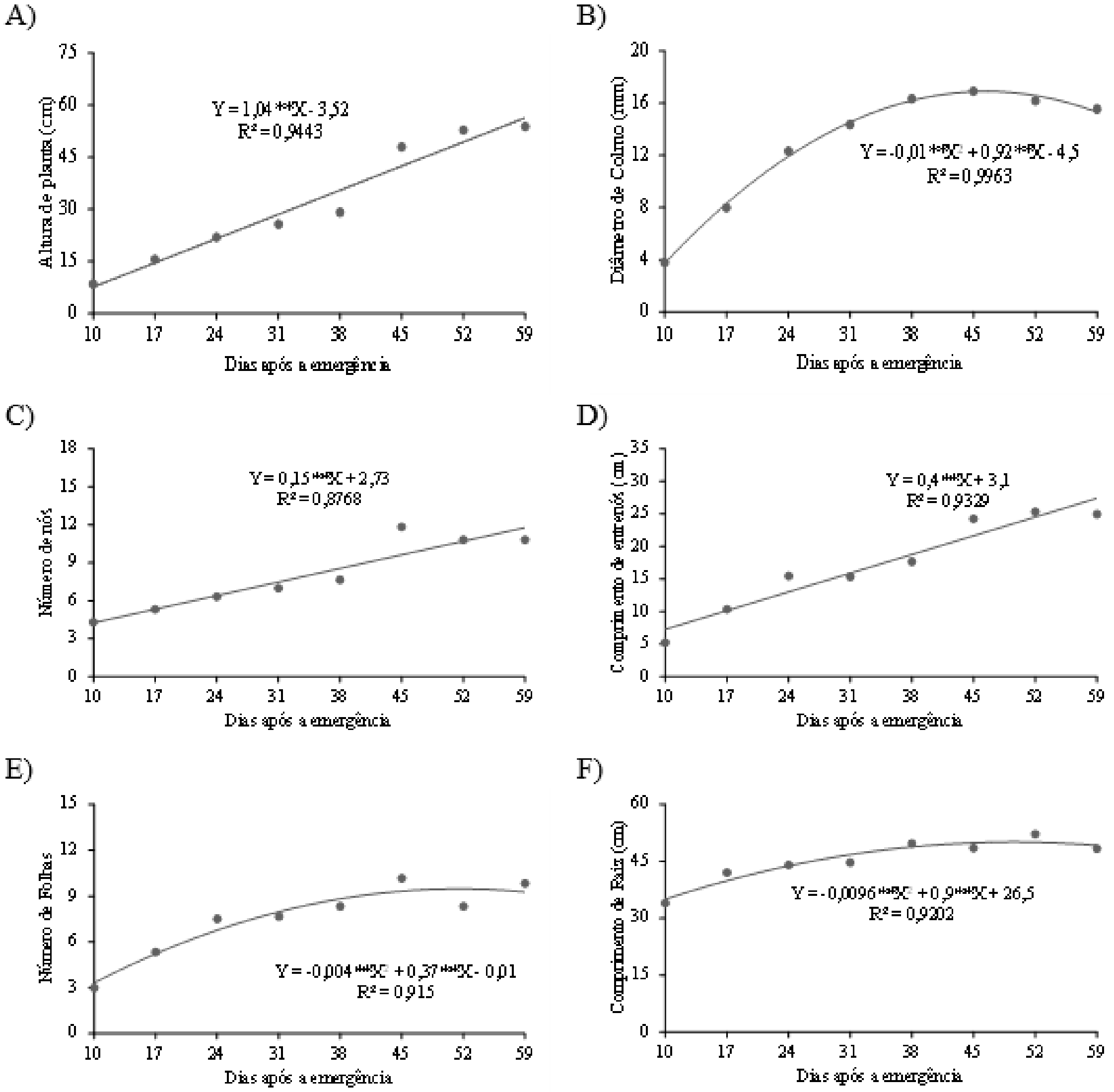
where:
AFE - specific leaf area ($cm^2\ g^{-1}$);
RPF - leaf weight ratio (gg^{-1});
RAF - leaf area ratio ($cm^2\ g^{-1}$);
MS_f - leaf dry matter mass (g);
MS_t - total dry matter mass of the plant (g).

The data were subjected to analysis of variance via the F test (*p<0.05*), and in cases of significance, regression analysis was performed for water replacement and the evaluation period via SISVAR® statistical software (Ferreira, 2011).

5 RESULTS AND DISCUSSION

The sorghum plant height as a function of days after emergence fit a linear model, with an ^{R2} of 94.43%, indicating that 5.57% of the variation in sorghum plant height was not explained by the variation in days after emergence (Figure 1A).

Figure 1. Plant height (A), stem diameter (B), number of nodes (C), internode length (D), number of leaves (E) and root length (F) as a function of days after emergence. ** significant at 1% probability according to F test.



Plant size is an important characteristic, as it is associated with stem resistance, susceptibility to lodging and breakage (Silva *et al.*, 2009; Oresca *et al.*, 2021).

The sorghum plant height linearly increased to 88.10%, which was observed between 10 and 59 days after emergence (DAE). The greater development of sorghum plants in height is a desirable characteristic, as tall plants tend to produce greater amounts of dry matter (Oliveira *et al.*, 2016).

The plant height of sorghum for each increase of 7 DAE increased by approximately 12.59%. Even under adverse conditions, sorghum crops generally present good growth and development, which results in a relatively high crop yield. Therefore, the increase in sorghum production is explained mainly by the high grain production potential, in addition to the extraordinary ability to withstand environmental stresses, such as frequent drought during the second harvest (Jordan *et al.*, 2017).

The sorghum stalk diameter as a function of days after emergence fit a quadratic model, with an R^2 of 99.63%, indicating that 0.37% of the variation in sorghum stalk diameter was not explained by the variation in days after emergence (Figure 1B). A maximum stalk diameter of approximately 16.65 mm was observed at 47 DAE, after which the stalk diameter stabilized.

Guimarães *et al.* (2019) reported that the sorghum varieties 2502-IPA, 2564-IPA, Ponta Negra and Qualimax presented the largest stem diameters, with averages between 14.83 and 16.32 mm.

The maximum sorghum stalk diameter observed at 47 DAE was 77.78, 50.45, 29.01, 13.45, 3.78, 2.10 and 10.09% greater than the sorghum stalk diameter observed at 10, 17, 24, 31, 38, 52 and 59 DAE, respectively. Stalk diameter is closely related to productivity, as it is a reserve organ for plants and is thus directly correlated with grain performance (Cruz *et al.*, 2008; Calone *et al.*, 2020).

The number of sorghum nodes as a function of days after emergence fit a linear model, with an R^2 of 87.68%, indicating that 12.32% of the variation in the number of sorghum nodes was not explained by the variation in days after emergence (Figure 1C). Silva (2017) also reported that the number of nodes as a function of days fit a linear model, with an R^2 of approximately 86%.

The number of nodes increased by 63.47% from 10 to 59 DAE, corresponding to an increase of approximately 12 nodes every 7 DAE. The number of sorghum nodes at each increase of 7 DAE shows an increase of approximately 9.07%. As the crop cycle phase progresses, an increase in dry matter accumulation and an increase in the number and length of internodes can be observed, benefiting growth and reflecting greater grain productivity (Cunha *et al.*, 2016; Silva, 2017).

The sorghum internode length as a function of days after emergence fit a linear model, with an R^2 of 93.29%, indicating that 6.71% of the variation in sorghum internode length was not explained by the variation in days after emergence (Figure 1D). The sorghum internode length increased by 73.41% from 10 to 59 DAE.

Sorghum crops under irrigation tend to have greater plant height, so the increase in internode length growth is a result of irrigation, since water plays a fundamental role in the greater elongation of internodes, resulting in taller plants under conditions favorable for plant growth (Shigaki *et al.*, 2004; Sousa *et al.*, 2020).

The internode length was adjusted to a linear model, with an increase of 2.9 cm observed every 7 DAE. The internode length of sorghum at each increase of 7 DAE increased by approximately 10.49%. A high crop growth rate results in greater internode length, which results in greater crop growth (Ghaffar *et al.* 2012; Mubarik *et al.*, 2022).

The number of sorghum leaves as a function of days after emergence fit a quadratic model, with an R^2 of 91.50%, indicating that 8.50% of the variation in the number of sorghum leaves was not explained by the variation in days after emergence. The maximum number of leaves, approximately 9, was recorded at 46 DAE (Figure 1E). Evaluating the leaf area according to the period of interest, i.e., days after emergence, the leaf area depends on the number of leaves, leaf size and vegetative stage, with the leaf area increasing to the maximum limit, at which point it remains active, starts to grow and then decreases due to leaf senescence (Manfron *et al.*, 2003; Calone *et al.*, 2020).

The maximum number of sorghum leaves observed at 46 DAE was 61.52, 40.07, 23.20, 10.92, 3.23, 1.59 and 7.65% greater than the number of sorghum leaves observed at 10, 17, 24, 31, 38, 52 and 59 DAE, respectively. The ability to maintain a greater number of leaves for a long period is an important indicator of more productive materials, as it indicates better performance of the photosynthetic apparatus.

Furthermore, the number of leaves is related to a plant's regeneration capacity throughout the crop cycle (Magalhães, 1979; Sousa *et al.*, 2020).

The sorghum root length as a function of days after emergence fit a quadratic model, with an ^{R2} of 92.02%, indicating that 7.98% of the variation in sorghum root length was not explained by the variation in days after emergence.

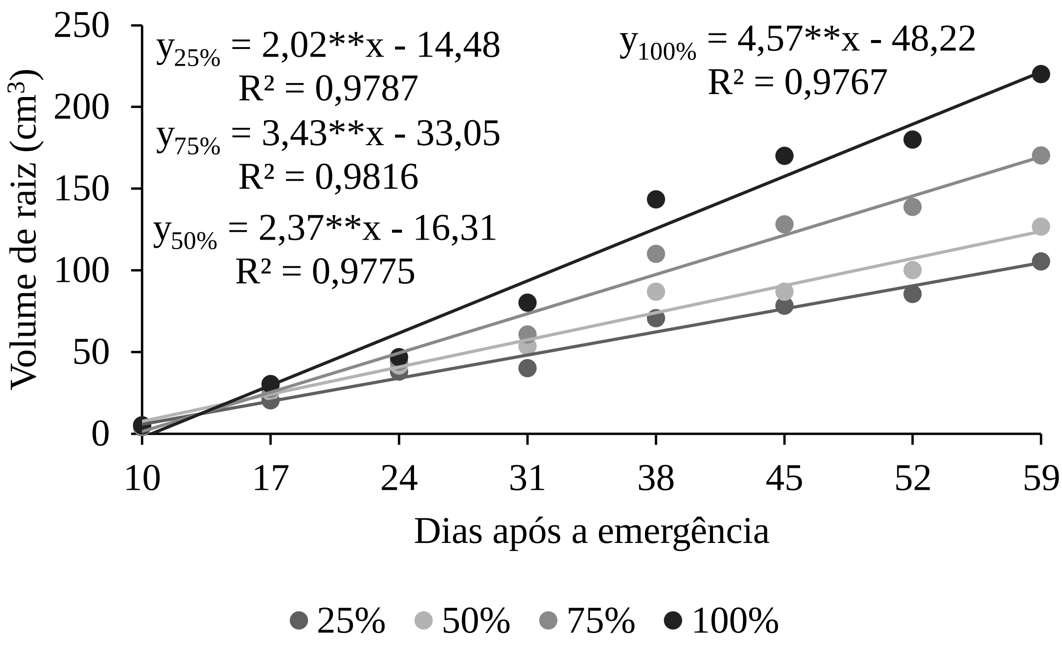
The evaluation of sorghum roots should be considered, considering that changes in the morphology of the root system, especially length and volume, are related to grain productivity. In addition, the length of sorghum roots is positively correlated with the total surface area and the surface area of fine roots (Negri *et al.*, 2014; Ali *et al.*, 2017).

The maximum root length was 47.59 cm at 47 DAE (Figure 1F). This is due to normal crop development, as root growth generally ends before flowering (Avila, 2018).

The maximum sorghum root length observed at 47 DAE was 27.42, 18.00, 10.55, 5.08, 1.58, 0.52 and 2.96% greater than the sorghum root length observed at 10, 17, 24, 31, 38, 52 and 59 DAE, respectively. Gírio *et al.* (2015) reported gains in plant height, stalk diameter, root length and stalk dry mass, concluding that adequate water replacement greatly favors crop growth and productivity.

The sorghum root volume as a function of days after emergence fit a linear model, with an average R2 of 97.86%, indicating that, on average, 2.14% of the variation in root volume was not explained by the variation in days after emergence (Figure 2).

Figure 2. Root volume as a function of days after emergence. ** significant at 1% probability according to F test.



Water availability generally has a major effect on crop growth, development and production components and has an important influence on root size and volume (Taiz; Zeiger, 2017).

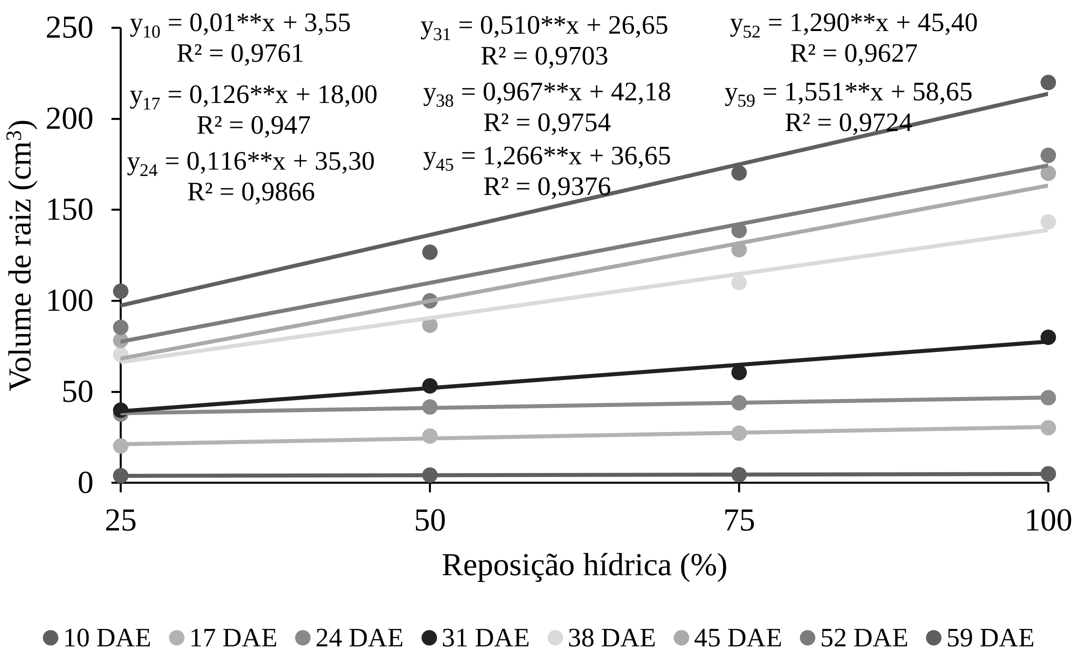
Comparing the evaluation periods of 10 and 59 DAE, increases in the sorghum root volume of approximately 94.54, 93.99, 99.24 and 99.46% were observed when water replacements of 25, 50, 75 and 100% were used, respectively.

The increase in the specific surface area of sorghum roots allows for greater water and nutrient absorption capacity from the soil, resulting in greater growth, development and crop yield (Quadros *et al.*, 2014; Silva *et al.*, 2024).

With each increase of 7 DAE, the root volume of sorghum increased by 13.50%, 13.43%, 14.18% and 14.45% when water replacement was applied at 25%, 50%, 75% and 100%, respectively. The volume of explored soil is essential for the effective absorption of water by roots, which reflects the better development of sorghum crops (Santos; Carlesso, 1998; Palacios-Diaz *et al.*, 2023).

The sorghum root volume as a function of water replacement was adjusted to a linear model, with an average R2 of 96.60%, indicating that, on average, 3.40% of the variation in root volume was not explained by the variation in water replacement (Figure 3).

Figure 3. Root volume as a function of water replacement. ** significant at 1% probability according to F test.



Changes in water status and variables related to the root system are decisive for biomass accumulation in *Sorghum bicolor plants* (Matos *et al.*, 2021).

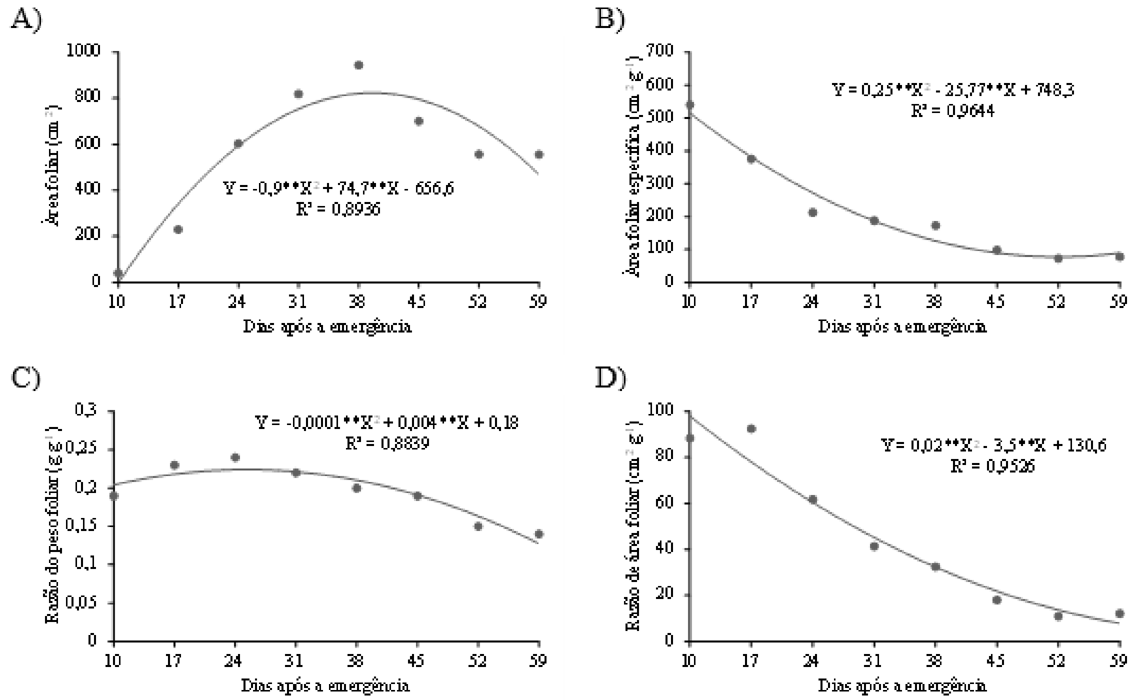
A comparison of water replacement percentages of 25 and 100% revealed increases in sorghum root volume of approximately 21.21, 30.94, 18.50, 49.25, 52.22, 58.16, 55.48 and 54.42% at 10, 17, 24, 31, 38, 45, 52 and 59 DAE, respectively.

Different levels of irrigation make it possible to modify the architecture of the plant's root, which causes an increase in root hairs, lateral roots and root length, which consequently generates an increase in the length of the root surface, enabling greater absorption of water and nutrients from the soil (Spaepen; Vanderleyden, 2011; Van Oosten *et al.*, 2017).

With each 25% increase in water content, the root volume of sorghum increased by 7.07, 10.31, 6.17, 16.41, 17.41, 19.39, 18.49 and 18.14% at 10, 17, 24, 31, 38, 45, 52 and 59 DAE, respectively. The limitation of sorghum crop growth is greater when plants are under a water replacement of less than 100%; therefore, smaller water volumes can cause variations in the root volume of the crop (Matos *et al.*, 2021; Silva *et al.*, 2024).

The maximum leaf area of 820 cm2 was detected 40 days after emergence (Figure 4A). An increase in leaf area indicates better plant growth, as it is one of the morphological parameters that directly reflects the development of sorghum, as it is used to estimate the photosynthetic capacity of plants and to predict dry matter production and productivity (Lessa *et al.*, 2018; Borrego *et al.*, 2021).

Figure 4. Leaf area (A), specific leaf area (B), leaf weight ratio (C) and leaf area ratio (D) as a function of days after emergence. ** significant at 1% probability according to F test.



The specific leaf area was adjusted to a quadratic model, where the maximum value was obtained at 10 DAE, and from 45 DAE onward, the stabilization of the specific leaf area of sorghum was observed, with a value of approximately 83 $cm^2\ g^{-1}$ (Figure 4B), that is, due to the increase in the dry mass of the leaves obtained by the expansion of the leaf area.

The specific leaf area is strongly correlated with the point of leaf turgor loss, which is an important parameter of water relationships (Bucci *et al.*, 2004; Oresca *et al.*, 2021).

The maximum leaf weight ratio of 0.22 $g\ g^{-1}$ was recorded at 25 DAE (Figure 4C). The high values of the leaf weight ratio at the beginning of the vegetative cycle and, subsequently, decrease are due to the direction of the action of the photosynthesized compounds to other regions of the plant (Aires, 2011; Dourado *et al.*, 2022).

The leaf area ratio showed the highest values between 10 and 45 DAE, followed by stabilization from 45 DAE onward, with the estimated leaf area ratio in this period being approximately 13.8 $cm^2\ g^{-1}$ (Figure 4D); this indicates that in this phase, most of the photosynthesized material is converted into leaves for greater capture of the available solar radiation.

The leaf area ratio decreases as plants grow, since with growth, the interference of upper leaves on lower leaves (self-shading) increases, and the useful leaf area tends to decrease (Benincasa, 2003; Calone *et al.*, 2020). Several authors suggest that the leaf area ratio reaches maximum values at the beginning of the vegetative cycle and subsequently decreases with plant maturation (Ferreira, 1996; Povh, 2004; Mubarik *et al.*, 2022).

6 CONCLUSION

The plant height, stem diameter, number of nodes, internode length, number of leaves, root length, leaf area, specific leaf area, leaf weight ratio and leaf area ratio of sorghum crops are not influenced by water replacement (25, 50, 75 and 100%).

The largest root volume of sorghum was detected with 100% water replacement at 10, 17, 24, 31, 38, 45, 52 and 59 days after emergence, indicating increases above 18%.

The root volume of sorghum irrigated every seven days after emergence showed an average increase of approximately 13.90%.

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8 REFERENCES

AIRES, RF **Assessment Ecophysiological analysis of castor bean in the environmental conditions of southern Rio Grande do Sul** . Thesis (Doctorate in Family Agricultural Production Systems) – Eliseu Maciel School of Agronomy, Federal University of Pelotas, Pelotas, p. 1-59, 2011.

ALI, F.; AHSAN, M.; ALI, Q.; KANWAL, N. Phenotypic stability of *Zea mays* grain yield and its attributing traits under drought stress. **Frontiers of Plant Science** , London, v. 8, article 1397, p. 1-11, 2017.

AVILA, RG **Induction of drought tolerance in sorghum grown under water restriction and supplemented with silicon and potassium nitrate in preflowering** . Thesis (Doctorate in Agronomy) – Universidade Federal de Lavras, Lavras, p.1-124, 2018.

BAZALUK, O.; HAVRYSH, V.; NITSENKO, V. Energy assessment of sorghum cultivation in southern Ukraine. **Agriculture** , Basel, vol. 11, no. 1, article 695, p. 1-22, 2021.

BENINCASA, MMP **Plant growth analysis (basics)** . 2nd ed. Jaboticabal: National Foundation for Education and Research, 2003.

BORREGO, FZ; GONZÁLEZ, AR; REYNA, VPA; CARRILLO, MG; MORENO, VMR; RANGEL, PP Effect of different levels of evapotranspiration on leaf area, surface temperature, water potential and yield in forage sorghum. **Terra Latinoamericana** , Chapingo, v. 39, no. 1, p. 1-14, 2021.

BUCCI, SJ; GOLDSTEIN, G.; MEINZER, FC; SCHOLZ, FG; FRANCO, AC; BUSTAMANTE, M. Functional convergence in hydraulic architecture and water relations of tropical savanna trees: from leaf to whole plant. **Tree Physiology** , Victoria, vol. 24, no. 8, p. 891-899, 2004.

CALONE, R.; SANOUBAR, R.; LAMBERTINI, C.; SPERANZA, M.; ANTISARI, LV; VIANELLO, G.; BARBANTI, L. Salt tolerance and Na allocation in *Sorghum bicolor* under variable soil and water salinity. **Plants** , Basel, vol. 9, no. 1, p. 1-20, 2020.

CRUZ, SCS; PEREIRA, FRS; BICUDO, SJ; ALBUQUERQUE, AW; SANTOS, JR; MACHADO, CG Nutrition of corn and Brachiaria decumbens grown in intercropping under different soil preparations. **Acta Scientiarum Agronomy** , Maringá, v. 30, n. 5, p. 733-739, 2008.

CUNHA, FN; SILVA, NF; SOUSA, AEC; TEIXEIRA, MB; SOARES, FAL; VIDAL, VM Yield of sugarcane submitted to nitrogen fertilization and water depths by subsurface drip irrigation. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande, v. 20, n. 9, p. 841-846, 2016.

DOURADO, PRM; SOUZA, ER; SANTOS, MAD; LINS, CMT; MONTEIRO, DR; PAULINO, MKSS; SCHAFFER, B. Stomatal Regulation and Osmotic Adjustment in Sorghum in Response to Salinity. **Agriculture** , Basel, vol. 12, no. 5, article 658, p. 1-12, 2022.

FERREIRA, DF Sisvar 5.3: a computer statistical analysis system. **Science and Agrotechnology** , Lavras , v. 35, n. 6, p. 1039-1042, 2011.

FERREIRA, E. **Osmotic adjustment and growth analysis of corn plants (*Zea mays* L.), as a function of potassium level and water stress.** 1966. Thesis (Doctorate in

Botany) – Faculty of Agronomic Sciences, São Paulo State University, Botucatu, p.1-100, 1996.

GHAFFAR, A.; EHSANULLAH; AKBAR, N.; KHAN, SH; JABRAN, K.; HASHMI, RQ; IQBAL, A.; ALI, MA Effect of trench spacing and micronutrients on growth and yield of sugarcane (*Saccharum officinarum* L.). **Australian Journal of Crop Science** , Kenmore, vol. 6, no. 1, p. 1-9, 2012.

GÍRIO, LAS; DIAS, FLF; REIS, VM; URQUIAGA, S.; SCHULTZ, N.; BOLONHEZI, D.; MUTTON, MA Growth-promoting bacteria and nitrogen fertilization on the initial growth of sugarcane from presprouted seedlings. **Brazilian Agricultural Research** , Brasília, DF, v. 50, n. 1, p. 33-43, Jan. 2015.

GUIMARÃES, MJM; SIMÕES, WL; OLIVEIRA, AR; ARAUJO, GGL; SILVA, Ê. FF; WILLADINO, LG Biometrics and grain yield of sorghum varieties irrigated with salt water. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande, v. 23, n. 4, p. 285-290, 2019.

JORDAN, RA; ALMEIDA, A.; QUEIROZ, MV; GOMES, EP; REZENDE, RK Energy balance of irrigated and rainfed sorghum production. **Agricultural Engineering** , Jaboticabal, v. 37, n. 5, p. 907-917, 2017.

KÖPPEN, W.; GEIGER, R. **Klimate der Erde** . Gotha: Verlag Justus Perthes. 1928.

LACERDA, MJR; FREITAS, KR; SILVA, JW Determination of forage dry matter by microwave and conventional methods. **Bioscience Journal** , Uberlândia, v. 25, n. 3, p. 185-190, 2009.

LESSA, BFT; SILVA, TM; DUTRA, AS; OLIVEIRA, AB Mathematical models for estimating total leaf area in sweet sorghum. **Energy in Agriculture** , Botucatu, v. 33, n. 2, p. 175-182, 2018.

LIMA, NRCB; SANTOS, PM; MENDONÇA, FC; ARAÚJO, LC Critical periods of sorghum and palisadegrass in intercropped cultivation for climatic risk zoning. **Brazilian Journal of Animal Science,** Viçosa, MG, v. 40, n. 1, p. 1452-1457, 2011.

MAGALHÃES, ACN Quantitative analysis of growth. *In* : FERRI, MG **Plant Physiology** . São Paulo: EPU: EDUSP, 1979. v. 1, p. 331-350.

MAGALHÃES, PC; ALBUQUERQUE, PEP; VIANA, JHM **Physiological response of sorghum to water stress in a greenhouse** . Sete Lagoas: Embrapa Corn and Sorghum, 2012. (Research and Development Bulletin, 46).

MAGALHÃES, PC; DURÃES, FOM **Ecophysiology of sorghum production** . Sete Lagoas: Embrapa Corn and Sorghum, 2003. (Technical communication, 87).

MANFRON, PA; DOURADO NETO, D.; PEREIRA, AR; BONNECARRÈRE, RAG; MEDEIROS, SLP; PILAU, FG Leaf area index model for corn crops. **Brazilian Journal of Agrometeorology** , Santa Maria, v. 11, n. 2, p. 333-342, 2003.

MARAFON, AC **Quantitative analysis of sugarcane growth** : an introduction to the practical procedure. 1st ed. Aracaju: Embrapa Tabuleiros Costeiros, p. 1-31, 2012.

MASOJIDEK, J.; TRIVEDI, S.; HALSHAW, L.; ALEXIOU, A.; HALL, DO The synergetic effect of drought and light stress in sorghum and pearl millet. **Plant Physiology** , Bethesda, vol. 96, no. 1, p. 198-207, 1991.

MATOS, FS; BASÍLIO, AAG; FURTADO, BN; GRATÃO, MS; BORGES, LP; AMORIM, VA Establishment of *Sorghum bicolor* L. plants under different water regimes. **Acta Iguazu** , Cascavel, v. 10, n. 1, p. 122-131, 2021.

MENDOZA-GRIMÓN, V.; AMORÓS, R.; FERNÁNDEZ-VERA, J. R; HERNÁDEZ MORENO, JM; PALACIOS-DÍAZ, MDP Effect of Different Water Quality on the Nutritive Value and Chemical Composition of Sorghum bicolor Payenne in Cape Verde. **Agronomy** , Basel, v. 11, n. 6, article 1091, p. 1-11, 2021.

MUBARIK, MK; HUSSAIN, K.; ABBAS, G.; ALTAF, MT; BALOCH, FS; AHMAD, S. Productivity of sorghum (*Sorghum bicolar* L.) at diverse irrigation regimes and sowing dates in semiarid and arid environments. **Turkish Journal of Agriculture and Forestry,** Amsterdam, v. 46, no. 1, p. 1-18, 2022.

NEGRI, BF; HUFNAGEL, BM; BERNARDINO, KC; PASTINA, MM; MAGALHÃES, JV; SOUSA, SM **Morphological characterization of the root system of recombinant inbred lines of sorghum under low phosphorus levels** . Sete Lagoas: Embrapa Corn and Sorghum, 2014. (Research and Development Bulletin, 98).

NIKOLAOU, G.; NEOCLEOUS, D.; CHRISTOU, A.; KITTA, E.; KATSOULAS, N. Implementing Sustainable Irrigation in Water-Scarce Regions under the Impact of Climate Change. **Agronomy** , Basel, v. 10, no. 8, article 1120, p. 1-33, 2020.

NOVAIS, RF; NEVES, JCL; BARROS, NF Testing in controlled environment . *In* : OLIVEIRA, AJ; GARRIDO, WE; ARAÚJO, JD; LOURENÇO, S. (coord.). **Soil fertility research methods** . Brasília, DF: Embrapa: SEA, 1991. p. 189-253.

OLIVEIRA, AB; GOMES FILHO, E. Germination and vigor of forage sorghum seeds under water and saline stress. **Brazilian Seed Journal ,** Londrina, v. 31, n. 3, p. 48-56, 2009.

OLIVEIRA, ECA; OLIVEIRA, RI; ANDRADE, BMT; FREIRE, FJ; LIRA JUNIOR, MA; MACHADO, PR Growth and dry matter accumulation in sugarcane varieties cultivated under full irrigation. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande, v.14, p.951-960, 2010.

OLIVEIRA, RMDE; ASPIAZÚ, I.; SILVA, KMJ; PORTUGAL, AF; SILVA, AF; CARVALHO, AJ Weed interference in sweet sorghum at different spacings in the semiarid region of Minas Gerais. **Brazilian Journal of Corn and Sorghum** , Sete Lagoas, v. 15, n. 3, p. 481-489, 2016.

ORESCA, D.; OLIVEIRA, AC; SILVA, TGF; PERSON, LGM; SOUZA, JCG; MACIEL, LH Agronomic performance of forage sorghum and millet grown under irrigation with saline water and nitrogen doses in the Brazilian semiarid region. **Research, Society and Development** , Vargem Grande Paulista, v. 10, no. 10, p. e359101018976, 2021.

PALACIOS-DIAZ, MDP; FERNÁNDEZ-VERA, JR; HERNÁNDEZ-MORENO, JM; AMORÓS, R.; MENDOZA-GRIMÓN, V. Effect of Irrigation Management and Water Quality on Soil and *Sorghum bicolor* Payenne Yield in Cape Verde. **Agriculture** , Basel , v. 13, n. 1, article 192, p. 1-18, 2023.

POVH, JA **Effects of plant growth regulators on the development of *Salvia officinalis* L. plants and on the**

production of essential oil . Dissertation (Master in Biological Sciences) – Institute of Biosciences, São Paulo State University, Botucatu, p. 1-100, 2004.

QUADROS, PD; ROESCH, LFW; SILVA, PRF; VIEIRA, VM; ROEHRS, DD; CAMARGO, FAO Field agronomic performance of corn hybrids inoculated with Azospirillum. **Ceres Journal** , Viçosa, v. 61, n. 2, p. 209-218, 2014.

RAKGOTHO, T.; NDOU, N.; MULAUDZI, T.; IWUOHA, EC; MAYEDWA, N.; AJAYI, RF Green synthesized zinc oxide nanoparticles mitigate salt stress in *Sorghum bicolor* . **Agriculture** , Basel, vol. 12, no. 5, article 597, p. 1-16, 2022.

RODRIGUES, JAS **Sorghum production system** . Sete Lagoas: Embrapa Corn and Sorghum. 2010. v. 2, n. 9.

SANTOS, RF; CARLESSO, R. Water deficit and the morphological and physiological processes of plants. **Brazilian Journal of Agricultural and Environmental Engineering ,** Campina Grande, v. 2 , n. 3, p. 287-294, 1998.

SHIGAKI, F.; FREITAS, N.; BERTO, A.; CEDDIA, MB; ZONTA, E.; LIMA, E. Influence of water stress on growth parameters, N accumulation and productivity of different sugarcane varieties in Miracema – RJ. **Revista Universitária Rural:** Série Ciências da Vida, Rio de Janeiro, v. 24, n. 1, p. 63-71, 2004.

SILVA, AG; BARROS, AS; SILVA, LHCP; MORAES, EB; PIRES, R.; TEIXEIRA, IR Evaluation of grain sorghum cultivars in the second crop in the southwest of the state of Goiás. **Tropical Agricultural Research** , Goiânia, v. 39, n. 1, p. 168-174, 2009.

SILVA, JC; SILVA, RF; SANTOS, VM; GIOVENARDI, AR; SILVA, DM; CANEPELLE, E.; SILVA, AP Plant growth-promoting bacteria in sorghum development in copper-contaminated soil. **Brazilian Journal of Environmental Sciences** , São Paulo, v. 59, p. e1660-1669, 2024.

SILVA, NF **Optimization of nitrogen sources and doses (15 N) in irrigated sugarcane in the cerrado** . 2017. Thesis (Doctorate in Agronomy/Agricultural Sciences) – Instituto Federal Goiano, Rio Verde, p. 1-114, 2017.

SOUSA, PGR; VIANA, TVA; CARVALHO, CM; SOUSA, JPF; CAMPOS, KC; AZEVEDO, BM Economic analysis of different irrigation depths in forage sorghum crops. **Brazilian Journal of Corn and Sorghum** , Sete Lagoas, v. 19, n. 1, p. 1-12, 2020.

SPAEPEN, S.; VANDERLEYDEN, J. Auxin and plant–microbe interactions auxin and plant–microbe interactions. **Cold Spring Harbor Perspectives in Biology** , Long Island, vol. 7, no. 3, p. 1-13, 2011.

TAIZ, L.; ZEIGER, E. **Plant physiology** . 6. ed. Porto Alegre: Artmed, 2017.

VALE, FXR; FERNANDES FILHO, EI; LIBERATO, JR **Quantification of diseases** – Quant. Software version 1.0.1. Viçosa: UFV, 2001.

VAN OOSTEN, MJ; PEPE, O.; PESCALE, S.; SILLETTI, S.; MAGGIO, A. The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. **Chemical and Biological Technologies in Agriculture** , Amsterdam, v. 4, no. 1, p. 1-12, 2017.