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Agronomic performance of wheat cultivars under water deficit in the Cerrado: adaptation and sustainability

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ABSTRACT

Wheat production faces limitations due to water constraints, in which climate variability impairs cultivation. This study evaluated the agronomic performance of three wheat cultivars (BRS264, BRS394 and BRS404) subjected to water stress gradients (12, 24, 36, 48 and 60 kPa) under controlled Cerrado conditions. The experiment, which was conducted in a greenhouse in Cuiabá, Brazil, used a randomized block design with a 5×3 factorial scheme and electrical capacitance sensors to monitor soil moisture. Shoot dry mass, root dry mass, grain yield and water use efficiency were analyzed. Tukey's tests and regression analyses revealed differences between cultivars: BRS394 presented better overall performance at 24 kPa, with increases of 20.1% in shoot dry mass, 70.8% in grain yield and 80% in water efficiency, whereas BRS264 presented better water efficiency at 12 kPa (40% increment). The comparative analysis revealed that 12 kPa resulted in less stress to the cultivars, with a significant decline in the parameters from 24 kPa, accentuating above 36 kPa. These results show that BRS394 adapts better to moderate water restriction (24 kPa), whereas BRS264 has better performance with greater water availability (12 kPa); both cultivars surpassed BRS404 in most of the parameters evaluated; and differentiated irrigation strategies are essential, prioritizing greater water availability for BRS264 and moderate restriction for BRS394 for the good development of wheat cultivation.

Keywords: Water, Efficiency, Yield, *Triticum aestivum*, Moisture.

Desempenho agronômico de cultivares de trigo sob déficit hídrico no Cerrado: adaptação e sustentabilidade

RESUMO

A produção de trigo enfrenta limitações devido a restrições hídricas, nas quais a variabilidade climática prejudica o cultivo. Este estudo avaliou o desempenho agronômico de três cultivares de trigo (BRS264, BRS394 e BRS404) submetidas a gradientes de tensão hídrica (12, 24, 36, 48 e 60 kPa) em condições controladas de Cerrado. O experimento, conduzido em casa de vegetação em Cuiabá-Brasil, utilizou delineamento em blocos casualizados em esquema fatorial 5×3, com sensores de capacitância elétrica para monitoramento da umidade do solo. Foram analisados massa seca da parte aérea, massa seca radicular, produção de grãos e eficiência no uso da água. Os testes de Tukey e análises de regressão revelaram diferenças entre cultivares: a BRS394 apresentou melhor desempenho geral a 24 kPa, com incrementos de 20,1% na massa seca da parte aérea, 70,8% na produção de grãos e 80% na eficiência hídrica, enquanto a BRS264 destacou-se na eficiência hídrica a 12 kPa (40% de incremento). A análise comparativa demonstrou que 12 kPa proporcionou menor estresse às cultivares, com declínio significativo nos parâmetros a partir de 24 kPa, acentuando-se acima de 36 kPa. Estes resultados evidenciam que: a BRS394 adapta-se melhor a restrição hídrica moderada (24 kPa), enquanto a BRS264 apresenta melhor desempenho com maior disponibilidade hídrica (12 kPa); ambas as cultivares superaram a BRS404 na maioria dos parâmetros avaliados; e estratégias de irrigação diferenciadas são essenciais, priorizando maior disponibilidade hídrica para BRS264 e restrição moderada para BRS394 para o bom desenvolvimento do cultivo de trigo.

Palavras-chave: Água, Eficiência, Produção, *Triticum aestivum*, Umidade.

1. Introduction

Bread wheat (*Triticum aestivum* L.), the second most produced cereal globally, is grown on approximately 228.9 million hectares and accounts for 80% of the world's wheat consumption (Liu et al., 2020). Its relevance encompasses human and animal food and industrial processing (Raper et al., 2019).

Wheat is essential for Brazilian agribusiness and is widely consumed, especially flour, in various foods. Its production is concentrated in the colder states of South China (Paraná and Rio Grande do Sul), which are responsible for more than 90% of national production, although Brazil still depends on imports to meet domestic demand (Chowdhury et al., 2017).

Genetic improvement programs seek to increase production and reduce this external dependence (Liu et al., 2022). Despite these challenges, Brazil has sought to increase production to decrease its dependence on imports and strengthen its position in the global market (Liu et al., 2022).

The wheat crop faces several challenges in Brazil, such as diseases, pests, industrial quality, management and climate. The latter climatic variations, including cold stress and heat stress (Langridge et al., 2022), impact wheat development and production. Monitoring climate conditions is essential for precision agriculture and for the adaptation of agricultural systems (Hachisuca et al., 2023).

Wheat in the Brazilian Cerrado presents unique opportunities and challenges. The Cerrado, a vast tropical savannah region in Brazil, is not traditionally a wheat-producing zone, mainly because of the hot and dry winter climate (Fava Roque et al., 2024). The limited availability of water during the wheat growing season in the Cerrado is an obstacle to increasing wheat production. Therefore, improving drought tolerance in wheat is a critical factor in unlocking the production potential of this region (Pereira et al., 2019).

Approximately 2.7 million hectares in the Cerrado are classified as favorable for wheat cultivation (Pasinato et al., 2018). The state of Mato Grosso, for example, has approximately 293 thousand irrigated hectares (ANA, 2021), and the cultivation of wheat under center pivots is a viable alternative to meet the water demand of crops (Cordeiro et al., 2015).

In this same region, in Rondonópolis, a city in Mato Grosso, the water consumption of the BRS254 and BRS394 cultivars can reach daily averages of 2.87 and 4.10 mm, 330 and 451 mm per cycle, respectively (Silva et al., 2021). These values highlight the importance of proper irrigation management, especially in areas where rainfall is insufficient during the dry season, without harming crucial moments of the crop. Irrigation in the stages of tapering, earing and filling the grain resulted in the highest yields (Rebeaud et al., 2019). In addition, the effects of abiotic stress, such as drought and salinity, are mitigated (Fan et al., 2023). This also improves the efficiency of the use of water and nutrients, and supplemental irrigation, which is based on the measurement of the soil water content, optimizes the use of water and nitrogen (Li et al., 2016).

Production in the Cerrado is directly linked to the ability of cultivars to adapt to water stress, which can significantly compromise the vegetative and reproductive development of the plant. These authors (Helman et al., 2019; Wato, 2021) demonstrated that water deficits during cultivation phases, such as germination and establishment, tillering, stem elongation, rubberizing, flowering, and granation, can cause significant damage and yield losses.

Helman et al. (2019) tested the Crop RS-Met model, which is based on actual evapotranspiration and soil moisture in the root zone, to predict rainfed wheat yield. In eight fields with different cultivars (*Triticum aestivum* L.) and water availability (185–450 mm), flowering was identified as the phase most sensitive to water deficit. The soil moisture at this stage was strongly correlated with the final yield ($R^2 = 0.90$), as it directly influenced potential grain fixation.

In view of this scenario, considering variables such as shoot and root dry mass, grain yield and water use efficiency, this study aimed to identify which cultivars present greater adaptations to water deficit through the performance of three wheat cultivars (BRS264, BRS394 and BRS404) recommended for the central region of Brazil under different water restriction conditions (12, 24, 36, 48 and 60 kPa).

2. Material and Methods

The study was conducted in a protected environment (greenhouse) in the experimental area of the Graduate Program in Tropical Agriculture, located at the University Campus of Cuiabá-MT of the Federal University of Mato Grosso (UFMT). The geographic coordinates of the location are 15°36' South Latitude and 56°3' West Longitude, with an altitude of 165 meters. Laboratory analyses were carried out at the Storage Technology Center of the Faculty of Agronomy and Animal Science of the same university.

The experimental period was from July 7 to November 4, 2020, with an average temperature of 28.5 °C and a relative humidity of 47.6%, and data were collected at the UFMT meteorological station. The climate of the place is classified as tropical savanna (Aw) with a dry season in winter according to the Köppen-Geiger climate classification.

Wheat finds better conditions in the Cerrado of Central Brazil in the months of May, June and July, which are favored by milder temperatures, and the climatic component is important for wheat in stages such as tillering and grain filling (Albrecht et al., 2006).

The soil used was classified as a dystrophic Red Latosol with a sandy loam texture, as described by Santos et al. (2018). It has the following chemical and particle size characteristics: pH ($CaCl_2$) = 5.00; Al^{3+} = 0.0 cmolc dm^{-3}; $H^+ + Al^{3+}$ = 3.17 cmolc dm^{-3}; CTC = 5.95 cmolc dm^{-3}; V (%) = 46.55; P = 12.9 mg dm^{-3}; K = 120.2 mg dm^{-3}; Ca^{2+} = 1.75 cmolc dm^{-3}; Mg^{2+} = 0.71 cmolc dm^{-3}; sand = 356.00 g kg^{-1}; silt = 130.00 g kg^{-1}; clay = 514.00 g kg^{-1}; and organic matter = 20.6 g dm^{-3}. The collection was carried out in the surface layer (0–0.20 m) in the experimental area of the Institute of Agrarian and Technological Sciences (ICAT) of the Federal University of Rondonópolis (UFR).

For soil correction, filler limestone (PRNT = 103%) was applied at a dose of 1.625 t ha^{-1}, resulting in a base saturation of 74.68% by the base saturation method, for 30 days, keeping the soil at 60% of the maximum soil water retention capacity in this period (Kroth et al., 2015).

Fertilization consisted of the application of 300 kg ha^{-1} of N, 206 kg ha^{-1} of K_2O and 472 kg ha^{-1} of P_2O_5, with urea, potassium chloride and simple superphosphate used as nutrient sources. Additionally, 100 kg ha^{-1} of FTE-BR12 was applied for micronutrient supplementation (9% Zn, 1.8% B, 0.8% Cu, 2% Mn, 3.5% Fe, 0.1% Mo). The soil was placed in polypropylene pots with a capacity of 5 dm³ (Fava Roque; Guimarães; Bonfim-Silva, 2024).

The cultivars used were BRS394, which has a cycle of 115 days, average height with an average productivity of 7,153 kg ha^{-1} (Albrecht et al., 2020); BRS264, which has a cycle of 105 days, average height with an average productivity of 7,229 kg ha^{-1} (Albrecht et al., 2021); and BRS 404, which has a cycle of 105–118 days, medium height, indicated for rainfed conditions with an average productivity of 2,800 kg ha^{-1} (Chagas et al., 2018).

The cultivars were created by the Brazilian Agricultural Corporation (Embrapa) for the Cerrado region of central Brazil, especially BRS264 and BRS394 for irrigation management in this region (Chagas et al., 2020).

Twenty seeds of each cultivar were sown per pot at a depth of 5 cm. During the first 15 days after emergence, the soil was maintained at field capacity, with the maximum water retention capacity in the soil in the pots as described previously (Bonfim-Silva et al., 2011), to ensure germination and seedling establishment. Seven days after emergence, thinning was performed, and five plants were left per pot.

The experimental design was randomized blocks (DBCs) in a 3x5 factorial scheme with three cultivars (BRS264, BRS404 and BRS394) and five water tensions (12, 24, 36, 48 and 60 kPa), for a total of five replications. The water treatments were started 15 days after emergence and maintained until the end of the experiment.

Soil moisture monitoring was performed via a capacitance sensor (ML3 model, Delta T), which was previously calibrated with tensiometers for the established water tensions (Silverio et al., 2017). Readings were taken at three distinct points on the surface of the vessel, and the average volumetric moisture was calculated. The soil water retention curve was adjusted via the van Genuchten model (1980) via soil water retention curve (SWCR) software (Dourado-Neto et al., 2000).

The volume of water needed for replacement was calculated via the method exemplified in Equations (1) to (4), considering the soil density (1.2 mg/cm³) and the difference between the desired volume and the current volume. To calculate the replacement of water in the vase, Equation (1) was used:

$$\theta v = \theta m * ds \quad (1)$$

where θm = moisture based on mass in decimals that are desired; θv = moisture based on volume in decimals that are desired; and ds = density of soil in pots (1.2 mg/cm^3). To calculate the mass of the moist soil, Equation 2 was used:

$$\theta m = msu - mss/mss \quad (2)$$

where msu = wet soil mass (kg) and mss = dry soil mass (kg). To calculate the desired volume of water, Equation 3 was used:

$$vad = msu/ds \quad (3)$$

where vad = the desired volume of water; ds = the potting soil density; and msu = the moist soil mass. To determine the current humidity, the same calculations were repeated, and the amount of water in the soil was varied for replacement; thus, the water level of each treatment was maintained. The volume of water replacement in the soil is obtained through Equation (4):

$$vr = vad - vaa \quad (4)$$

where vr = the volume of water replaced in the soil (ml), vad = the desired water volume and vaa = the current water volume (ml).

When the result of the calculation was positive, replacement was performed, and when it was negative, water replacement was not performed in the soil. Plants that showed symptoms of water deficiency (dull, curled or poorly turgored leaves) (Lamaoui et al., 2018) were temporarily transferred to a voltage of 12 kPa until recovery, after which they returned to their original treatments.

Phytosanitary management was carried out every month during the cycle, the control of invasive plants was performed manually, and pests such as stink bug (*Nezara viridula*; Diceraeus melacanthus; Diceraeus furcatus) cows (Diabrotica speciosa) and thrips (Frankliniella schultzei) were controlled with insecticides based on thiamethoxam + lambda-cyhalothrin (370 mL^{-1} a.i. ha^{-1}). For the management of diseases such as yellow spot (Pyrenophora tritici-repentis) and blast (Magnaporthe oryzae), difenoconazole (275 mL^{-1} a.i. ha^{-1}) and tebuconazole (160 mL^{-1} a.i. ha^{-1}) were used.

The evaluations were carried out on an average of three plants per pot. At the end of the crop cycle, the following variables were evaluated: shoot dry mass, which was weighed on a semianalytical scale in shoots (leaves, stems and ears) after being dried in a forced circulation oven at 65 °C to a constant mass in Kraft paper bags; root dry mass, which was the weight of the root part on an analytical scale in grams after being dried in a forced circulation oven at 65 °C to constant mass; and grain production, which was the mass of grains harvested in each experimental unit, weighed on an analytical scale and corrected for 13% moisture (Brasil, 2009). The efficiency of water use was defined as the ratio between agricultural production and the amount of water used (Wang et al., 2024), which was calculated as the ratio between grain production and the volume of water applied in each pot.

The data were subjected to analysis of variance (ANOVA), and the means were compared via Tukey's test ($p<0.05$) for qualitative factors and via regression analysis for quantitative factors. All the statistical analyses were performed via R software at https://www.r-project.org/ via the ExpDes.pt version 1.2.1 package.

3. Results and Discussion

The effects of the treatments on all the variables were analyzed, the first being the dry mass of the aerial part, which was an interaction between the factors. The unfolding of the cultivar factor at each moisture level made it possible to verify that, by the test of averages, there was a difference only in the level of 24 kPa of moisture tension (Table 1).

The cultivar BRS394 had the highest average value, which was statistically equal to that of BRS264, with a 20.1% increase in relation to BRS404, the only cultivar indicated for rainfed conditions (Chagas et al., 2018); at the other moisture levels, the cultivars did not differ (Table 1).

The moisture levels of each cultivar were broken down through quadratic regressions (Figure 1). The cultivars are responsive to increases in water (water stress), and the quadratic regression equations reveal distinct patterns of response to water stress among the cultivars. BRS394 had the highest coefficient of determination ($R^2 = 0.79$), indicating that 79% of the variation in dry mass was explained by the model, which suggests a positive relationship between the dry mass of the aerial part and variations in water stress (Figure 1).

BRS404 showed a lower fit ($R^2=0.63$), indicating greater sensitivity to uncontrolled variables. BRS394 was stable in terms of dry mass production at intermediate stresses (24–36 kPa), whereas BRS404 sharply decreased from 24 kPa. The convex curves (positive quadratic terms) revealed that the cultivars maintained yield under mild stress (12–24 kPa), with a significant decline only above 36 kPa, corroborating the superiority of BRS394 under water stress conditions, which is in line with the differentiated responses of wheat to drought reported by Khadka et al. (2020).

Humidity proved to be a limiting factor, with lower dry mass values at voltages above 36 kPa. The negative coefficients of the linear term (-3.13, -2.57 and -3.16) indicate the negative impact of the increase in water tension on biomass production, with greater decreases in the BRS264 and BRS404 cultivars (Figure 1). According to Zhang et al. (2018), water stress can be classified as mild (10–35 kPa), moderate (35–55 kPa) or severe (>55 kPa). In the same study, water deficit progressively reduced wheat biomass by 11.0% (mild), 21.0% (moderate) or 34.7% (severe), indicating a greater impact according to the intensity of the stress.

Drought during tillering reduces stem growth, the number of effective tillers, and plant height (Sarto et al., 2017), with variable impacts according to genotype and stress intensity. Studies report declines of 2–24% and 1–16% in wheat height under 30% and 70% field capacity, respectively, during stem elongation (Qadir et al., 2016), in addition to the generalized reduction in tiller number (Maqbool et al., 2015; Abid et al., 2018).

Water deficit reduces the growth of the aerial part of a plant (Saeidi et al., 2015; Ding et al., 2018), as it redirects photoassimilates to the roots (Khadka et al., 2020). The height and leaf area of drought-tolerant species are limited to conserve water (Su et al., 2019), resulting in lower aerial shoot dry mass.

Ptošková et al. (2022) grew wheat seedlings in sandy soil under controlled conditions, suspending irrigation in half of the plants after the emergence of the third leaf. After 5 days, the fourth leaf of plants under water deficit conditions was 31% shorter than that of irrigated plants, which was associated with a decrease in bioactive gibberellins in the leaf base. This process promotes the accumulation of DELLA proteins, which inhibit shoot growth, stomatal opening, and sweating (Nir et al., 2017). In addition, under water deficit, stomatal closure reduces transpiration and CO_2 fixation, limiting photosynthesis and the chlorophyll index (Zulkiffal et al., 2021).

Table 1. Average shoot dry mass (g) of wheat plants as a function of five soil moisture tensions in the different cultivars.

Cultivar	Soil moisture tension (kPa)				
	60 kPa	48 kPa	36 kPa	24 kPa	12 kPa
	Dry mass (g)				
BRS 264	0.90 a	0.68 a	0.77 a	1.27 ab	2.81 a
BRS 394	1.03 a	0.99 a	0.96 a	1.59 a	2.54 a
BRS 404	0.70 a	0.96 a	1.23 a	0.96 b	2.90 a
CV (%)					14.28%
F Test					0.043*

*Significant to the analysis of variance with a 5% probability of error level. Consecutive means with the same letter (vertical) were not significantly different according to Tukey's test (p<0.05).

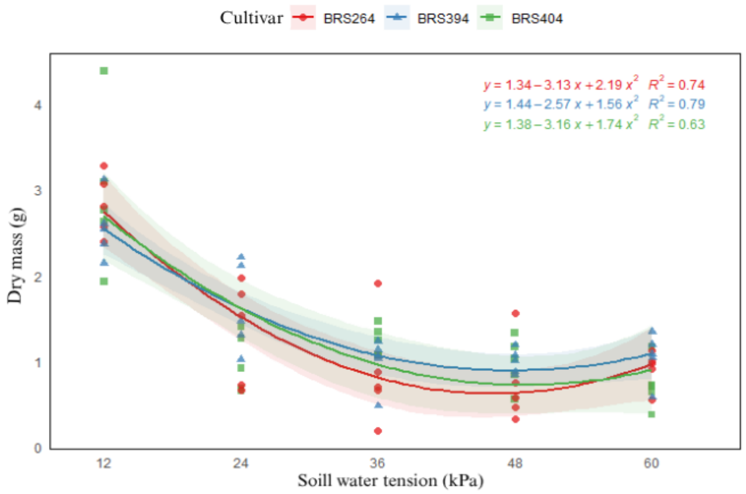

Figure 1. Quadratic relationship between the soil water tension (kPa) and shoot dry mass (g) of the wheat cultivars BRS264 (red), BRS394 (blue) and BRS404 (green). The curves represent the second-degree polynomial fit for each cultivar, with specific equations and coefficients of determination (R^2). The marked points (●, ▲, ■) indicate the values observed for each water tension (12, 24, 36, 48 and 60 kPa), and the shaded area around the curves represents the 95% confidence interval.

In contrast, increased irrigation increases shoot dry matter production (Jha et al., 2019). Compared with traditional methods, cultivation techniques, such as furrows and beds with rainfall collection combined with 150 mm of deficient irrigation and 200 mm of simulated rainfall, improve dry matter translocation by 31.6% (Ali et al., 2018).

In terms of the response of the dry mass of the roots, there was no interaction between the factors or even the effect of moisture, only the effect of the cultivar, with the highest accumulation, 75.86%, of the cultivar BRS 394 in relation to the cultivar BRS404, which had the lowest dry mass of the roots (Table 2).

The relatively high root dry mass of BRS394 reflects its ability to adapt to moderate water stress, increasing water absorption in soils with intermediate moisture contents (Tavares et al., 2023). This characteristic increases its water extraction capacity compared with that of other cultivars (Zhang et al., 2015), corroborating its prioritization of resource allocation for roots under water deficit (Table 2).

Under water deficit, plants alter their growth, prioritizing root development over shoot development to maximize water absorption. This adaptation is associated with an increase in bioactive gibberellins in the roots, which maintain their growth even under stress conditions (Ptoškova et al., 2022).

A deep and well-developed root system is crucial for water efficiency and drought tolerance in crops such as wheat. Narrow-angled roots and vertical growth reach wetter soil layers under water stress, directly influencing growth and productivity (Wasaya et al., 2018). Dense, sloping lateral roots improve water absorption at greater depths, whereas long and thin primary roots facilitate penetration into dry and compacted soils, increasing the surface water and nutrient absorption (Khadka et al., 2020).

Abscisic acid is an essential phytohormone in the response of plants to drought, regulating stomatal closure and stress genes (Khadka et al., 2020). Under drought conditions, its levels increase dramatically in all plant tissues, particularly in the roots. In wheat seedlings, abscisic acid concentrations increase 79-fold at the root tips and 219-fold at the remaining root tissue during water stress (Ptoškova et al., 2022). Under induced drought, abscisic acid promoted root growth (Awan et al., 2021).

In terms of grain production, there was an interaction between the factors, and the cultivar factor at each moisture level significantly differed in the levels of

24 and 60 kPa of water tension in the soil, highlighting the cultivar BRS394, which presented the highest average 24 and 60 kPa moisture contents (Table 3). In the analysis of the quantitative effect by means of regressions, a decrease in production was observed under conditions of stresses greater than 24 kPa (Figure 2).

The results revealed that all the wheat cultivars presented significant quadratic responses to variations in soil water tension, with coefficients of determination (R^2) ranging from 0.69-0.74 (Figure 2). The cultivar BRS404 showed the greatest fit of the model (R^2 = 0.74), indicating that 74% of the variation in yield can be explained by changes in water tension. On the other hand, the BRS264 and BRS394 cultivars presented slightly lower R^2 values (0.70 and 0.69, respectively), suggesting that other unmeasured factors may have influenced their production.

Table 2. Means of root dry mass (g) of wheat plants as a function of five soil moisture stresses in the different cultivars.

Cultivar	Root Dry Mass (g)
BRS 264	0.55 b
BRS 394	1.45 a
BRS 404	0.35 b
CV	14.28%
F Test	0.043*

**Significant in the analysis of variance with a level of 1% probability of error. Consecutive means with the same letter (vertical) were not significantly different according to Tukey's test (p<0.05).

Table 3. Average grain yield (g) per experimental unit as a function of five soil moisture stresses in the different cultivars.

Cultivar	Soil moisture tension (kPa)				
	60	48	36	24	12
	Grain yield (g)				
BRS 264	0.08 ab	0.10 a	0.07 a	0.07 ab	1.72 a
BRS 394	0.12 a	0.11 a	0.10 a	0.24 a	1.10 a
BRS 404	0.00 b	0.01 a	0.01 a	0.01 b	1.60 a
CV					44.32%
F Test					0.003*

*Significant to the analysis of variance with a 5% probability of error level. Consecutive means with the same letter (vertical) were not significantly different according to Tukey's test (p<0.05).

The negative coefficients of the linear term (-2.33, -1.59 and -2.34) reveal a negative impact of the increase in water tension on production, revealing a direct negative relationship between grain yield and soil water tension, with the difference between the cultivars BRS264 and BRS404 in relation to BRS394 being (-70.83 and -95.83%, respectively) (Figure 2).

The analysis of the quadratic equations revealed that the maximum grain yield occurred under conditions of lower water stress (12–24 kPa), with a sharp decline from 36 kPa. Compared with the other cultivars, cultivar BRS394 presented the lowest coefficients in linear and quadratic terms (-1.59 and +1.04), indicating a response to the increase in water tension. In contrast, the cultivars BRS264 and BRS404 presented decreases in grain yield under greater stress (decreasing linear coefficients of -2.33 and -2.34), reflecting greater sensitivity to water scarcity. Under these conditions, BRS394 can be more productive under conditions of moderate stress, whereas the other cultivars are more dependent on adequate irrigation.

With BRS404, despite showing a good relationship with the statistical model, its grain production was limited in relation to water restriction. On the other hand, BRS394 presented higher averages than the other cultivars did, especially in the range of 24–36 kPa. These results have important practical implications for the water management of wheat because, in the experiment carried out, the results of the cultivar BRS394 obtained superior results, with increases greater than 70% in relation to those of the other cultivars under moderate deficit of water restriction.

More restrictive treatments in intermediate phenological stages cause a decrease in grain production (Gull et al., 2019). During critical stages of crop development, such as reproduction and grain formation, wheat grain production can be reduced by up to 92%, which is related to the severity of water availability stress during postanthesis and grain formation (Ahmed et al., 2019). A similar difference of 95% in the grain production of BRS394 in relation to the BRS404 cultivar was reported in the present study.

In the reproductive phase, the decline in transpiration due to water deficit in the maturation period results in a reduction in grain, grain weight, ear and production and identification; the characterization and screening of broad-based genetic resources through conventional breeding, together with the use of modern genetic protocols and agronomic management, will pave the way for efficient and accurate screening at each phonological stage of wheat (Zulkiffal et al., 2021).

Drought severity is the condition that causes the greatest reduction in grain yield in wheat (Fathi and Tari, 2016).

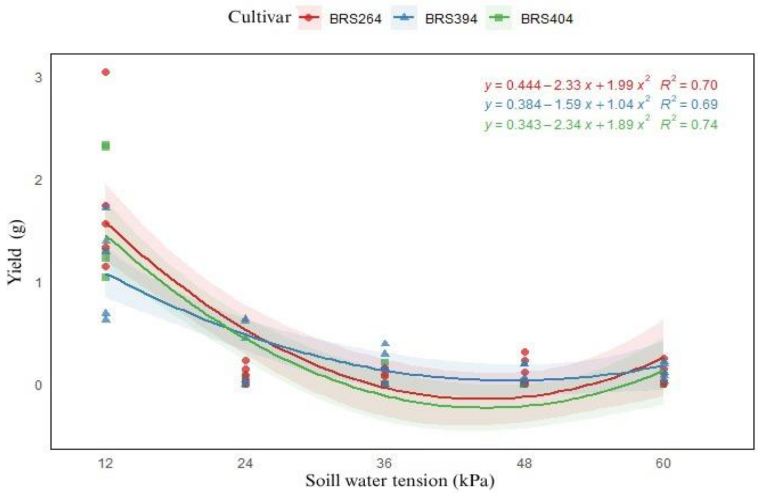

Figure 2. Quadratic relationship between soil water tension (kPa) and yield per pot (g) of wheat cultivars BRS264 (red), BRS394 (blue) and BRS404 (green). The curves represent the second-degree polynomial fit for each cultivar, with specific equations and coefficients of determination (R^2). The marked points (●, ▲, ■) indicate the values observed for each water tension (12, 24, 36, 48 and 60 kPa), and the shaded area around the curves represents the 95% confidence interval.

Water stress reduces turgor pressure and stomatal closure and limits the CO_2 supply, thereby inhibiting the dark reactions of photosynthesis and decreasing the maximum net photosynthetic rate (Ibrahimova et al., 2021).

The restriction of the activity of the Rubisco enzyme and the capacity for regeneration further exacerbate this phenomenon. Notably, the effects of water stress on the light response of plants can vary according to the species (Chen et al., 2025), making it possible to highlight BRS 394 as the most stable cultivar because of its ability to moderate water deficit in relation to other cultivars.

The decrease in the production of BRS394 under water stress of 36 kPa, compared with 12 kPa, indicates financial risks in extreme droughts in the Cerrado, a biome marked by rainfall seasonality (García-Núñez et al., 2019). In this region, the high evaporative demand, due to low humidity and high temperatures, accelerates soil water depletion (Vieira et al., 2019), which has a direct impact on wheat revenue, according to the National Supply Company (CONAB), estimated at R$ 5,200-6,800/ha in the Midwest (CONAB, 2023).

The BRS264 cultivar, in turn, showed greater resilience at 12 kPa, suggesting that complementary irrigation may be feasible to ensure production during critical periods, such as the results obtained with a new drip irrigation standard (ReDiP) that promotes increased wheat production, reduces implementation costs and optimizes water distribution (Li et al., 2025).

The efficiency of water use in grain production was influenced by the interaction between the factors, and the cultivar factor at each moisture level differed, as shown in Table 4.

The efficiency of water use in grain production was influenced by the interaction between the factors, and the unfolding of the cultivar factor at each moisture level provided a difference only at the levels of 12 and 24 kPa of soil moisture, highlighting the cultivar BRS264 with the highest average at the level of 12 kPa and BRS394 at 24 kPa, which are the most efficient in the use of water in these respective humidity ranges.

The quantitative effect, expressed in Figure 3, demonstrates a response to the increase in water from 24 kPa of tension, and the results demonstrate distinct patterns of water efficiency among wheat cultivars subjected to different water stresses. The cultivar BRS404 presented the best fit of the quadratic model (R^2 = 0.72), demonstrating a more consistent relationship between water tension and water use efficiency.

BRS394 presented the lowest R^2 (0.48), indicating that only 48% of the variation in its water efficiency was explained by the model, suggesting the influence of other factors. BRS264 had an intermediate R^2 (0.67), indicating a greater response to water stress (Figure 3). BRS264 stood out for its highest quadratic coefficient (+0.309), reflecting sensitivity to water variation, whereas BRS394 (+0.128) showed a more stable response. The negative linear coefficients (-0.316, -0.246 and -0.293) confirmed that greater water availability increased efficiency (Figure 3).

Low water stress and high irrigation frequency increase water use efficiency (Mondal et al., 2020). Similar results were reported by Li et al. (2021), who reported an increase in grain production and water efficiency during the first increase in irrigation, a trend that was also observed in the present study (Figure 3).

Table 4. Average grain yield efficiency per liter of water used ($g.L^{-1}$) in wheat plants subjected to five soil moisture stresses.

Cultivar	Soil moisture tension (kPa)				
	60	48	36	24	12
	Water use efficiency in grain production ($g.L^{-1}$)				
BRS 264	0.03 a	0.05 a	0.03 a	0.02 b	0.28 a
BRS 394	0.05 a	0.05 a	0.06 a	0.10 a	0.20 b
BRS 404	0.00 a	0.02 a	0.02 a	0.01 b	0.20 a
CV					66.46%
F Test					0.034*

*Significant to the analysis of variance with a 5% probability of error level. Consecutive means with the same letter (vertical) were not significantly different according to Tukey's test (p<0.05).

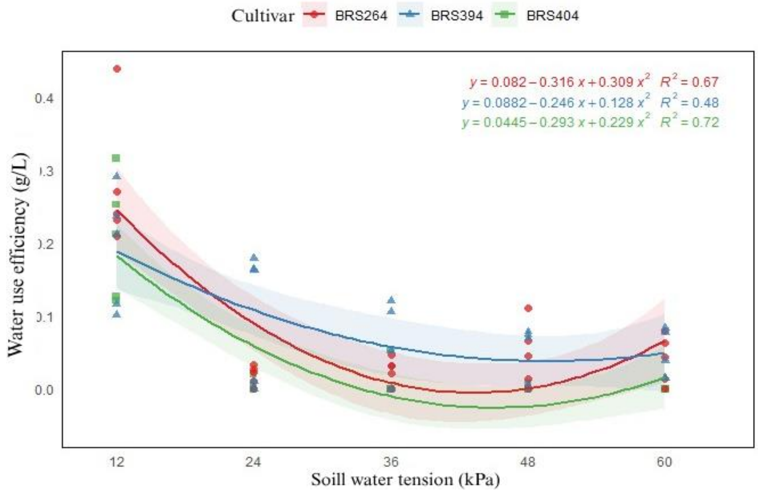

Figure 3. Quadratic relationship between soil water tension (kPa) and water use efficiency (g/L) of the wheat cultivars BRS264 (red), BRS394 (blue) and BRS404 (green). The curves represent the second-degree polynomial fit for each cultivar, with specific equations and coefficients of determination (R^2). The marked points (●, ▲, ■) indicate the values observed for each water tension (12, 24, 36, 48 and 60 kPa), and the shaded area around the curves represents the 95% confidence interval.

Irrigation, sprinkling, flooding, and drip methods, on the appropriate schedule, when the field capacity is less than 60%, have the potential to balance the optimal yield and water use efficiency (Jha et al., 2019), with capacities close to 24 to 36 kPa and mild to moderate water deficit (Zhang et al., 2018), depending on soil variations.

An analysis of the equations revealed that all the cultivars had positive quadratic coefficients and that the water use efficiency of the cultivars increased to a certain point of water tension before declining, a condition that was not explored within the treatments of the present study. Wang (2017) reported that increased moisture reduces water efficiency, which is the opposite of the results of the present study, because, compared with our treatments, there was supplemental irrigation, precipitation, and lower water restriction in the work done in northern China.

The genetics of cultivars significantly alter the response to water deficit, according to a study that used seventy lines of emmer wheat germplasm (*Triticum dicoccum* L.) to determine genetic diversity and response to drought-related traits (Sharada et al., 2025). Studies in wheat associate the expression of genes that activate water conservation pathways with moderate soil moisture stress (Fathi & Tari, 2016).

Tavares et al. (2023) reported that BRS394 maintains greater CO_2 assimilation and stomatal conductance under moderate water stress (24 kPa), whereas BRS264 performs better under optimal conditions (12 kPa). This adaptation is associated with stomatal regulation by abscisic acid, which, under drought, induces protein degradation and the accumulation of solutes such as proline, improving stress tolerance (Sewelam et al., 2017).

BRS394 performed better than the other cultivars under moderate water restriction (24 kPa), whereas BRS264 stood out under conditions of relatively high water availability (12 kPa), reflecting different strategies for photoassimilated allocation. BRS394 presented greater root dry mass, favoring water extraction in soils with moderate restrictions (Zhang et al., 2015), whereas BRS264 presented greater water efficiency under ideal conditions, directing resources to grain production (Jha et al., 2019).

For production systems, BRS264 is indicated in favorable water conditions, whereas BRS394 is better adapted to regions with water variability. These results highlight the importance of selecting cultivars according to regional water availability, aiming at efficiency in the use of resources and sustainability in the Cerrado.

4. Conclusions

The water tension of 12 kPa minimized the stress in the cultivars, with a significant reduction in the parameters from 24 kPa, intensifying above 36 kPa. BRS394 showed better performance in terms of biomass and water efficiency at 24 kPa, whereas BRS264 stood out in terms of water efficiency at 12 kPa, surpassing BRS404. The results indicate different irrigation strategies: moderate restriction (24 kPa) for BRS394 and greater water availability (12 kPa) for BRS264.

Authors' Contribution

All authors contributed equally to this manuscript. Paulo Otávio Aldaves dos Santos Guedes, Tonny José Araújo da Silva, Carlos Caneppele and Edna Maria Bonfim da Silva data analysis, writing, and review. Paulo Otávio Aldaves dos Santos Guedes conducted the experiment and collected the data.

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Bibliographic References

Abid, M., Ali, S., Qi, L.K., Zahoor, R., Tian, Z., Jiang, D., Snider, J. L., Dai, T. 2018. Physiological and biochemical changes during drought and recovery periods at the tillering and jointing stages in wheat (*Triticum aestivum* L.). Scientific Reports, 8:4615. https://doi.org/10.1038/s41598-018-21441-2

Ahmed, I., Ullah, A., Rahman, M.H.U., Ahmad, B., Wajid, S. A., Ahmad, A., Ahmed, S. 2019. Climate change impacts and adaptation strategies for agronomic crops. Climate Change and Agriculture, 1-14. https://doi.org/10.5772/intechopen.82697

Ali, S., Xu, Y., Jia, Q., Ahmad, I., Wei, T., Ren, X., Zhang, P., Din, R., Cai, T., Jia, Z. 2018. Cultivation techniques combined with deficit irrigation improves winter wheat photosynthetic characteristics, dry matter translocation and water use efficiency under simulated rainfall conditions. Agricultural Water Management, 201, 207-218. https://doi.org/10.1016/j.agwat.2018.01.017

Albrecht, J.C. 2021. Wheat cultivar BRS 264: precocity, industrial quality and high yields for the cerrado of Central Brazil (Technical Circular 49). Embrapa Cerrados.

Albrecht, J.C., Chagas, J.H., Sobrinho, J.S., Scheeren, P.L., Fronza, V. 2020. Trigo BRS 394: cultivar para o Cerrado do Brasil Central (Circular Técnica 44). Embrapa Cerrados.

Albrecht, J.C., Silva, M.S., Andrade, J.M.V., Scheeren, P.L., Trindade, M.G., Sobrinho, J.S., Sousa, C.N.A., Braz, A.J.B. P., Ribeiro Júnior, W.Q., Sousa, M.A., Fronza, V., Yamanaka, C.H. 2006. Wheat BRS 264: Early cultivar with high grain yield indicated for the Cerrado of Central Brazil (Documents 174). Embrapa Cerrados.

Awan, S.A., Khan, I., Rizwan, M., Zhang, X., Brestic, M., Khan, A., El-Sheikh, M.A., Alyemeni, M.N., Ali, S., Huang, L. 2021. Exogenous abscisic acid and jasmonic acid restrain polyethylene glycol-induced drought by improving the growth and antioxidative enzyme activities in pearl millet. Physiologia Plantarum, 172(2), 809–819. https://doi.org/10.1111/PPL.13247

Bonfim-Silva, E.M., Silva, T.J.A., Cabral, C.E.A., Kroth, B. E., Rezende, D. 2011. Initial development of grasses subjected to water stress. Caatinga Magazine, 24(2), 180-186.

Chagas, J.H., Sobrinho, J.S., Pires, J.L.F., Silva, M.S., Albrecht, J.C., Cunha, G.R, Moresco, E.R. 2018. Informações fitotécnicas para potencializar o desempenho produtivo da cultivar de trigo BRS 404 no Cerrado do Brasil Central (Circular Técnica 33). Embrapa Trigo.

Chen, F., Zhang, K., Yan, S., Wang, R., Wang, H., Zhao, H., Qi, Y., Yang, Y., Wei, X., Tang, Y. 2025. Response of photosynthesis response to light and CO_2 concentration in spring wheat under progressive drought stress. BMC Plant Biology, 25(1), 324. https://doi.org/10.1186/s12870-025-06355-7

CONAB. COMPANHIA NACIONAL DE ABASTECIMENTO, 2023. Monitoramento da safra de grãos brasileira: safra 2023/24, Brasília, Ministério da Agricultura, Pecuária e Abastecimento, 11(12).

Cordeiro, M.B., Dallacort, R., Freitas, P.S.L., Junior, S.S., Santi, A., Fenner, W. 2015. Aptidão agroclimática do trigo para as regiões de Rondonópolis, São José do Rio Claro, São Vicente e Tangará da Serra, Mato Grosso, Brasil. Revista Agro@mbiente On-line, 9(1), 96-101. https://doi.org/10.18227/1982-8470ragro.v9i1.2177

Dourado-Neto, D., Nielsen, D.R., Hopmans, J.W., Reichardt, K., Bacchi, O.O.S., Lopes, P.P. 2000. Software to model soil water retention curves (SWRC, version 2.00). Scientia Agrícola, 57(1), 191-192. https://doi.org/10.1590/S0103-90162000000100031

Fan, Y., Wang, X., Chen, R., Dang, H., Liu, H. 2023. Differences in Water Consumption and Yield Characteristics among Winter Wheat (*Triticum aestivum* L.) Varieties under Different Irrigation Systems. Applied Sciences, 13(7), 4396. https://doi.org/10.3390/app13074396

Fathi, A., Tari, D. B. 2016. Effect of drought stress and its mechanism in plants. International Journal of Life Sciences, 10(1), 1-6. https://10.3126/ijls.v10i1.14509

García-Núñez, C., Pirela, M., Fariñas, M., Azócar, A. 2019. Seasonal patterns of gas exchange and water relations in juveniles of two Neotropical savanna tree species differing in leaf phenology. Acta Oecologica, 95, 57-67. https://doi.org/10.1016/j.actao.2019.01.005

Gull, A., Lone, A.A., Wani, N.U.I. 2019. Biotic and abiotic stresses in plants. Abiotic and Biotic Stress in Plants, 1-19. https://doi.org/ 10.5772/intechopen.85832

Hachisuca, A.M.M., Abdala, M.C., Souza, E.G., Rodrigues, M., Ganascini, D., Bazzi, C.L. 2023. Growing degree-hours and degree-days in two management zones for each phenological stage of wheat (*Triticum aestivum* L.). International Journal of Biometeorology, 67(7), 1169–1183. https://doi.org/10.1007/s00484-023-02486-4

Helman, D., Lensky, I.M., Bonfil, D.J. 2019. Early prediction of wheat grain yield production from root-zone soil water content at heading using Crop RS-Met. Field Crops Research, 232, 11–23. https://doi.org/10.1016/j.fcr.2018.12.003

Ibrahimova, U., Zivcak, M., Gasparovic, K., Rastogi, A., Allakhverdiev, S.I., Yang, X., Brestic, M. 2021. Electron and proton transport of electrons and protons in wheat exposed to salt stress: is the increase in proton conductivity of the thylakoid membrane responsible for the decrease in photosynthetic activity in sensitive genotypes? Research on Photosynthesis, 150, 195–211. https://doi.org/10.1007/s11120-021-00853-z

Jha, S.K., Ramatshaba, T.S., Wang, G., Liang, Y., Liu, H., Gao, Y., Duan, A. 2019. Response of growth, yield and water use efficiency of winter wheat to different irrigation methods and scheduling in North China Plain. Agricultural Water Management, 217, 292-302. https://doi.org/10.1016/j.agwat.2019.03.011

Khadka, K., Earl, H.J., Raizada, M.N., Navabi, A. 2020. A physio-morphological trait-based approach for breeding drought tolerant wheat. Frontiers in Plant Science, 11, 715. https://doi.org/10.3389/fpls.2020.00715

Langridge, P., Alaux, M., Almeida, N.F., Ammar, K., Baum, M., Bekkaoui, F., Bentley, A.R., Beres, B.L., Berger, B., Braun, H.J., Brown-Guedira, G., Burt, C.J., Caccamo, M.J., Cattivelli, L., Charmet, G., Civáň, P., Cloutier, S., Cohan, J.-P., Devaux, P.J., Doohan, F.M., Dreccer, M.F., Ferrahi, M., Germán, S.E., Goodwin, S.B., Griffiths, S., Guzmán, C., Handa, H., Hawkesford, M.J., He, Z., Hutter, E., Ikeda, T.M., Kilian, B., King, I.P., King, J., Kirkegaard, J.A., Lage, J., Le Gouis, J., Mondal, S., Mullins, E., Ordon, F., Ortiz-Monasterio, J.I., Özkan, H., Öztürk, I., Pereyra, S.A., Pozniak, C.J., Quesneville, H., Quincke, M.C., Rebetzke, G.J., Reif, J.C., Saavedra-Bravo, T., Schurr, U., Sharma, S., Singh, S.K., Singh, R.P., Snape, J.W., Tadesse, W., Tsujimoto, H., Tuberosa, R., Willis, T.G., Zhang, X. 2022. Meeting the Challenges Facing Wheat Production: The Strategic Research Agenda of the Global Wheat Initiative. Agronomy, 12(11), 2767. https://doi.org/10.3390/agronomy12112767

Li, J.P., Zhang, Z., Yao, C.S., Liu, Y., Wang, Z.M., Fang, B.T., Zhang, Y.H. 2021. Improving winter wheat grain yield and water-/nitrogen-use efficiency by optimizing the micro-sprinkling irrigation amount and nitrogen application rate. Journal of Integrative Agriculture, 20(2), 606-621. https://doi.org/10.1016/S2095-3119(20)63407-4

Li, L., Wang, Z., Wan, W., Li, Z., Cai, J., Zhou, Q., Huang, M., Zhong, Y., Wang, X., Jiang, D. 2025. A novel, ridged enlarging lateral space drip irrigation pattern (ReDiP) for high-yield and WUE spring wheat in Xinjiang, China. Field Crops Research, 328, 109921. https://doi.org/10.1016/J.FCR.2025.109921

Liu, F., Kang, Z., Tan, X., Fan, Y., Tian, H., Liu, T. 2020. Physiology and defense responses of wheat to the infestation of different cereal aphids. Journal of Integrative Agriculture, 19(6), 1464–1474. https://doi.org/10.1016/s2095-3119(19)62786-3

Liu, Q., Zhang, X., Su, Y.H., Zhang, X.S. 2022. Mechanisms of Cold Signaling in Wheat (*Triticum aestivum* L.). Life, 12, 700. https://doi.org/10.20944/preprints202204.0117.v1

Maqbool, M.M., Ali, A., Haq, T., Majeed, M.N., Lee, D.J. 2015. Response of spring wheat (*Triticum aestivum* L.) to induced water stress at critical growth stages. Sarhad Journal of Agriculture, 31, 53–58. https://doi.org/10.23959/SFOWJ-1000003

Mondal, S., Dutta, S., Crespo-Herrera, L., Huerta-Espino, J., Braun, H.J., Singh, R.P. 2020. Fifty years of semi-dwarf spring wheat breeding at CIMMYT: Grain yield progress in optimum, drought and heat stress environments. Field Crops Research, 250, 107757. https://doi.org/10.1016/j.fcr.2020.107757

Nir, I., Shohat, H., Panizel, I., Olszewski, N., Aharoni, A., Weiss, D. 2017. The tomato DELLA protein PROCERA acts in guard cells to promote stomatal closure. The Plant Cell, 29(12), 3186-3197. https://doi.org/10.1105/tpc.17.00542

Pasinato, A., Cunha, G.R., Fontana, D.C., Monteiro, J.E.B.A., Nakai, A.M., Oliveira, A.F. 2018. Potential area and limitations for the expansion of rainfed wheat in the Cerrado biome of Central Brazil. Pesquisa Agropecuária Brasileira, 53(7), 779–790. https://doi.org/10.1590/s0100-204x2018000700001

Pereira, J.F., Cunha, G.R., Moresco, E.R. 2019. Improved drought tolerance in wheat is required to unlock the production potential of the Brazilian Cerrado. Crop Breeding and Applied Biotechnology, 19(2), 217–225. https://doi.org/10.1590/1984-70332019v19n2r30

Ptošková, K., Szecówka, M., Jaworek, P., Tarkowská, D., Petřík, I., Pavlović, I., Novák, O., Thomas, S.G., Phillips, A. L., Hedden, P. 2022. Changes in the concentrations and transcripts for gibberellins and other hormones in a growing leaf and roots of wheat seedlings in response to water restriction. BMC Plant Biology, 22(1), 284. https://doi.org/10.1186/s12870-022-03667-w

Qadir, S.A., Khursheed, M., Huyop, F. 2016. Effect of water stress on the morphology, growth and yield of six bread wheat cultivars (*Triticum aestivum* L.). ZANCO Journal of Pure and Applied Sciences, 28, 37–48.

Raper, T.B., McClure, M.A., Butler, S., Yin, X., Blair, R. 2019. Impacts of Single- and a Multiple-Species Cover Crop on Soybean Relative to the Wheat-Soybean Double Crop System. Crop, Forage Turfgrass Management, 5(1), 180104. https://doi.org/10.2134/cftm2018.12.0104

Rebeaud, S.G., Jaylet, A., Cotter, P.-Y., Camps, C., Christen, D. 2019. A Multi-Parameter Approach for Apricot Texture Analysis. Agriculture, 9(4), 73. https://doi.org/10.3390/agriculture9040073

Roque, W.F., Guimarães, S.L., Bonfim-Silva, E.M. 2024. Bactérias Nodulíferas Coinoculadas em Cultivares de Trigo Cultivado em Latossolo Vermelho do Cerrado. Ensaios e Ciência: Ciências Biológicas, Agrárias e da Saúde, 28(3), 369–375. https://doi.org/10.17921/1415-6938.2024v28n3p369-375

Saeidi, M., Ardalani, S., Jalali-Honarmand, S., Ghobadi, M. E., Abdoli, M. 2015. Evaluation of drought stress at vegetative growth stage on the grain yield formation and some physiological traits as well as fluorescence parameters of different bread wheat cultivars. Acta Biologica Szeged, 59, 35–44.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araujo Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Brazilian Soil Classification System. 5th ed, rev. and exp., Brasília, DF: Embrapa.

Sarto, M.V.M., Sarto, J.R.W., Rampim, L., Bassegio, D., Costa, P.F., Inagaki, A.M. 2017. Phenology of wheat and productivity under drought: a review. Australian Journal of Crop Science, 11(8), 941–946. https://doi.org/10.21475/ajcs17.11.08.pne351

Sharada, H.B., Uday, G., Gopalreddy, K., Priyanka, K., Vishwasgowda, C., Nandeesh, J.R. 2024. Genetic diversity and trait association research in emmer wheat (*Triticum dicoccum* L.) germplasm lines for moisture stress. Genetic Resources and Crop Evolution, 72, 5515–5528. https://doi.org/10.1007/S10722-024-02286-8

Silverio, J.M., Silva, T.J.A., Bonfim-Silva, E.M., Iaia, A.M., Duarte, T.F., Pires, R.C.M. 2017. Drought tolerance of the sugar cane varieties during the initial development. Australian Journal of Crop Science, 11(6), 711-715. https://doi.org/10.21475/ajcs.17.11.06.p437

Su, Y., Wu, F., Ao, Z., Jin, S., Qin, F., Liu, B., Pang, S., Liu, L., Guo, Q. 2019. Evaluating maize phenotype dynamics under drought stress using terrestrial lidar. Plant Methods, 15, 11. https://doi.org/10.1186/s13007-019-0396-x

Tavares, C.J., Ribeiro Junior, W.Q., Ramos, M.L.G., Pereira, L.F., Muller, O., Casari, R.A.C.N., Sousa, C.A.F., Silva, A.R. 2023. Water Stress Alters Physiological, Spectral, and Agronomic Indexes of Wheat Genotypes. Plants, 12(20), 3571. https://doi.org/10.3390/plants12203571

Van Genuchten, M.T. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44(5), 892-898.

Vieira, E.A., Galvão, F.C.A., Barros, A.L. 2019. Influence of water limitation on the competitive interaction between two Cerrado species and the invasive grass *Brachiaria brizantha* cv. Piatã. Plant Physiology and Biochemistry, 135, 206-214. https://doi.org/10.1016/j.plaphy.2018.12.002

Wang, D. 2017. Water use efficiency and optimal supplemental irrigation in a high yield wheat field. Field Crops Research, 213, 213-220. https://doi.org/10.1016/j.fcr.2017.08.012

Wang, T., Sun, S., Yin, Y., Zhao, J., Tang, Y., Wang, Y., Gao, F., Luan, X. 2024. Status of crop water use efficiency evaluation methods: A review. Agricultural and Forest Meteorology, 349, 109961. https://doi.org/10.1016/j.agrformet.2024.109961

Wato, T. 2021. Growth and Yield Performance of Wheat (*Triticum aestivum* L.) to under Water Stress Conditions. Agricultural Science Digest - A Research Journal, 41(2), 301-306. https://doi.org/10.18805/ag.D-289

Zhang, J., Zhang, S., Cheng, M., Jiang, H., Zhang, X., Peng, C., Lu, X., Zhang, M., Jin, J. 2018. Effect of drought on agronomic traits of rice and wheat: A meta-analysis. International Journal of Environmental Research and Public Health, 15(5), 839. https://doi.org/10.3390/ijerph15050839

Zhang, X., Zhang, X., Liu, X., Shao, L., Sun, H., Chen, S. 2015. Incorporating root distribution factor to evaluate soil water status for winter wheat. Agricultural Water Management, 153, 32-41. https://doi.org/10.1016/j.agwat.2015.02.001

Zulkiffal, M., Ahsan, A., Ahmed, J., Musa, M., Kanwal, A., Saleem, M., Anwar, J., ur Rehman, A., Ajmal, S., Gulnaz, S., Javaid, M.M. 2021. Heat and Drought Stresses in Wheat (*Triticum aestivum* L.): Substantial Yield Losses, Practical Achievements, Improvement Approaches, and Adaptive Mechanisms, in: Hossain, A. (Ed.), Plant Stress Physiology. IntechOpen. https://doi.org/10.5772/intechopen.92378