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Tolerance of high-yielding corn hybrids to drought stress during the early growth stage[1]

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ABSTRACT - The early seedling stage is one of the most vulnerable and critical growth stages in the plant life cycle and determines the final plant stand and yield. Corn hybrids have distinct degrees of drought tolerance, and exploiting this characteristic is important to enhance agricultural production in many tropical regions of the world. Fourteen corn hybrids commonly grown in the central-western region of Brazil, in Cassilândia, Mato Grosso do Sul, were assessed for drought tolerance during the early plant growth stage. Plants were grown in the Plant Ecophysiology Laboratory under non-stressful (control) and stressful (moderate drought) conditions for 28 days. Drought stress was induced with an –0.30 MPa iso-osmotic solution prepared with polyethylene glycol (PEG-6000). The emergence rate, seedling length, and seedling dry matter were measured, and then drought tolerance indexes were calculated. Our results showed that root length is an important morphological trait for plant adaptation to drought stress conditions. Therefore, plant breeding programs should select corn genotypes with longer roots to develop commercial hybrids with superior performance under limited soil water availability. The corn hybrids FS 575 PWU, GNZ 7757 VIP3, LG 36745 PRO4, and MG 545 PWU have greater tolerance to drought stress and are the most suitable genotypes to be grown in conditions of low soil water availability. The AG 8088 PRO2 corn hybrid has greater susceptibility to drought stress and should not be recommended for cultivation in conditions of reduced soil water availability.

Key words: Osmotic potential. Tolerance index. Water stress. *Zea mays*.

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INTRODUCTION

Corn (*Zea mays* L.) is one of the most important cereal crops in Brazil and the world, especially due to its use in food, animal feed/forage, ethanol production, and other industrial products. However, in many situations, adverse environmental conditions have limited crop growth and yield. Among the unfavorable conditions, drought stress is one of the most critical environmental factors that can compromise seed germination and limit the growth and yield potential of corn crops in many world regions (Gopalakrishna *et al*., 2023; Kim; Lee, 2023; Walne *et al*., 2024). Therefore, to ensure food supply for a growing world population, studies that aim to identify hybrids with greater drought tolerance are important to enhance crop yield in tropical regions with a high probability of dry spells and drought.

In general, drought stress early in the growing season has been less detrimental to corn yield than during the pollination and grain-filling phases (Çakir, 2004; Pandit *et al*., 2017). However, prolonged or severe drought conditions early in the season can significantly reduce crop yields. Corn seeds need to imbibe 30-35% of their weight in water to initiate the germination process (Bewley *et al*., 2013). Low water availability at the time of corn sowing can inhibit and delay the seed germination process, causing irregular plant stands in the field (Queiroz *et al*., 2019). Additionally, early-season drought stress can reduce corn plant size and leaf area, inhibit root growth, and impair nutrient absorption, negatively impacting ear length, number of kernels per ear, and lower crop grain yield (Çakir, 2024; Kim; Lee, 2023; Walne *et al*., 2024).

Under drought conditions, corn plants have a series of morphological, physiological, and metabolic changes (Gopalakrishna *et al*., 2023; Walne *et al*., 2024), which constitute drought tolerance mechanisms. Morphological responses of corn plants may depend on genotype, plant development stage, duration, and intensity of water stress (Çakir, 2004; Pandit *et al*., 2017). During the initial growth stage of corn, the main drought tolerance strategies include increasing the photoassimilate allocation to the root system, maintenance of chlorophyll content, leaf growth inhibition, reduced leaf area, leaf rolling, and intermediate metabolite synthesis, which are responsible for osmotic adjustment and maintenance of plant turgidity (Pandit *et al*., 2017; Walne *et al*., 2024). These responses are part of plant strategies that aim to mitigate the adverse effects of water stress and, therefore, constitute drought tolerance mechanisms.

Understanding drought stress tolerance and adaptation mechanisms based on plant morphological changes is a key factor in improving crop management in the field and helping corn genetic breeding programs develop commercial hybrids with greater water use efficiency and improved performance in limited water conditions. Although the exact mechanisms of corn drought tolerance are not fully understood, some morphophysiological characteristics have been considered useful in identifying drought-sensitive or tolerant corn hybrids (Pandit *et al*., 2017). Walne *et al.* (2024) pointed out that greater drought tolerance of sugarcane genotypes is associated with greater water use efficiency, reduced leaf area, and the greater ability of roots to explore deeper soil layers in drought conditions.

Due to the importance of corn cultivation for Brazil and the world, and the recent changes in rainfall patterns in many regions of the world, this study was conducted to evaluate the degree of drought tolerance of 14 corn hybrids during the initial plant growth stage.

MATERIAL AND METHODS

Study site, plant material and stress treatments

The study was conducted at the Plant Ecophysiology Laboratory, State University of Mato Grosso do Sul (UEMS), in Cassilândia, MS, Brazil (19°05'30.0"S and 51°48'55.0"W). Seeds from a total of 14 commercial corn hybrids from the Brazilian Cerrado region were purchased from the agricultural seed market in the municipalities of Chapadão do Sul and Cassilândia, State of Mato Grosso do Sul, Brazil. Before starting the study, the water content, the mass of thousand seeds, and the germination rate were determined as described in the Rules for Seed Analysis (Brasil, 2009). The main characteristics of corn seeds are shown in Table 1.

The seeds were first sterilized with 2% (v/v) sodium hypochlorite (NaOCl) solution for 5 minutes and immediately rinsed three times with sterile water as used by Queiroz *et al.* (2019). The sterilized seeds were shade-dried at laboratory room temperature for 48 hours and then placed to germinate under non-stressful (control) and stressful conditions (moderate drought stress).

The drought stress was induced by exposing the seeds to a solution with an osmotic potential of –0.30 MPa prepared with polyethylene glycol (PEG-6000). The concentration of PEG-6000 required to obtain the solution was determined by the equation of Michel and Kaufmann (1973): $\Psi s = [-(1.18 \times 10^{-2}) \times C - (1.18 \times 10^{-4}) \times C^2 + (2.67 \times 10^{-4}) \times C \times T + (8.39 \times 10^{-7}) \times C^2 \times T]/10$, where Ψs is the osmotic potential (MPa), C is the concentration (g L^{-1} of PEG-6000) and T is the temperature (°C). Distilled water with an osmotic potential of 0.00 MPa was used as a control treatment.

Table 1 - Agronomic characteristics, thousand seed weight (1,000-SW), water content (WC), and germination rate (GR) of the 14 corn hybrids used in this study

N°	Hybrid	Agronomic characteristics				1,000-SW (g)	WC (%)	GR (%)
		Biotechnological Event	Maturation Cycle	Plant Height (cm)	Yield Potential			
1	AG 8701 PRO4	VT PRO 4®	Early	242	High	384	12.3	98
2	LG 36745 PRO4	VT PRO 4®	Early	240	High	379	12.0	92
3	GALO VIP3	Agrisure Viptera® 3	Early	225	High	365	12.6	100
4	ONÇA PRO2	VT PRO 2®	Early	230	High	362	12.5	92
5	AS 1868 PRO4	VT PRO 4®	Early	238	High	379	13.0	86
6	MG 545 PWU	Power Core® Ultra	Early	233	High	365	11.9	94
7	AG 8700 PRO4	VT PRO 4®	Early	235	High	356	12.5	92
8	B 2800 VYHR	Leptra®	Early	272	High	372	12.1	88
9	DKB 390 PRO4	VT PRO 4®	Early	245	High	388	12.7	96
10	DKB 360 PRO3	VT PRO 3®	Early	247	High	390	12.4	84
11	STINE 9075 VIP3	Agrisure Viptera® 3	Early	266	High	360	12.8	94
12	FS 575 PWU	Power Core® Ultra	Early	245	High	340	11.8	100
13	GNZ 7757 VIP3	Agrisure Viptera® 3	Early	240	High	355	12.6	98
14	AG 8088 PRO2	VT PRO 2®	Early	250	High	330	12.1	88

Treatments were arranged in a completely randomized design (CRD), in a 2 × 14 factorial scheme: two stress treatments (control or water stress) and fourteen corn hybrids, with four replicates.

Plant emergence and growth conditions

Four sub-samples of 50 seeds were sown in plastic boxes (44 × 30 × 7.5 cm) containing sterilized sand, at a depth of 2.0 cm. The sand used as substrate was previously sieved through a mesh with a diameter of 0.05 to 0.8 mm. The sand was then moistened with distilled water (control) or PEG-6,000 solution (drought stress) in a proportion of 60% of the substrate's retention capacity (Brasil, 2009), equivalent to 80 mL of aqueous solution for each kilogram of sand. The plastic boxes were kept in laboratory conditions using artificial light supplementation with red (620 - 630 nm) and blue (455 - 475 nm) wavelengths at the ratio of 85% (red) and 15% (blue) from light-emitting diodes (LEDs) at a light intensity of 240 ± 90 μmol m^{-2} s^{-1} and photoperiod of 12/12 h (light/darkness), for 28 days. The temperature during the experimental bioassay varied from 22.8 °C to 29.4 °C, with an average value of 25.2 °C.

Measurement of emergence, plant growth, and tolerance indexes

At 15 days after sowing, the emergence rate of corn seedlings was recorded. After 28 days of exposure to drought stress, ten seedlings per replicate were randomly chosen to measure the length and dry matter of the shoot and roots. The shoot length, root length, and total plant length were measured using a meter scale. The shoot dry matter, root dry matter, and total plant dry matter were recorded in analytical balance (±0.0001 g) after oven drying at 85 °C for 48 h.

The data of emergence rate, plant length, and plant dry matter were used to calculate the stress tolerance indexes (STI) as used by Zuffo *et al*. (2020): ΔSTI = [(Δ under stressful conditions/Δ under control conditions) × 100], where, Δ are the dependent variables measured in corn plants (i.e., emergence (E), shoot length (SL), root length (RL), total plant length (TL), shoot dry matter (SDM), root dry matter (RDM), and total plant dry matter (TDM)).

The original data of emergence rate, plant length, and plant dry matter were also used to calculate the plant vigor indexes under drought stress. The plant length vigor index (LVI) and plant weight vigor index (WVI) under stressful conditions were calculated by the following equations proposed by Abdul-Baki and Anderson (1973): LVI = [total plant length (m) × emergence rate (%)] and WVI = [total plant dry weight (g) × emergence rate (%)].

Statistical analysis

The data were previously tested for homoscedasticity of variances (Levene test; $p > 0.05$) and normality of residues (Kolmogorov–Smirnov test; $p > 0.05$) and, then were submitted to analysis of variance (ANOVA). The means of stress tolerance indexes for corn hybrids were compared by the Scott-Knott test at the 0.05 level of confidence. The analyses were performed using Rbio® software version 140 for Windows (Rbio Software, UFV, Viçosa, MG, BRA).

The identification of tolerant or susceptible hybrids to drought stress was performed based on all stress tolerance indexes (STI), using the ranking method, as showed by Zuffo *et al*. (2020). A hybrid with the highest value for each of the STI received a rank score of 1, while the hybrid with the lowest value for each of the STI received a rank score of 14. The mean rank ($\overline{R}$) and standard deviation of ranks (SDR) of all stress tolerance criteria were then calculated. The discrimination of corn hybrids regarding their tolerance degree to drought stress was performed based on the mean rank score of each genotype, considering the values of the quartiles that divide the 14 possible positions (i.e. 14 corn hybrids) into four equal parts. A hybrid with a mean rank ($\overline{R}$) lower than the value of the first quartile (< 4.2 points) is classified as tolerant (T); a hybrid with an $\overline{R}$ between the first and second quartiles (4.3 to 7.5 points) is classified as moderately tolerant (MT); a hybrid with an $\overline{R}$ between the value of the second and third quartiles (7.6 to 10.7 points) is classified as moderately susceptible (MS); and the group of drought-susceptible hybrids (S) is represented by genotypes with an $\overline{R}$ higher than the value of the third quartile (> 10.8 points).

Hierarchical clustering analysis (HCA) of 14 corn hybrids based on the Euclidean distance method and unweighted pair group method with arithmetic mean (UPGMA) was performed using the Rbio® software version 140 for Windows (Bhering, 2017). The optimal number of drought tolerance groups formed in the dendrogram was defined by Mojena's criterion (Mojena, 1977). This criterion is based on computing the highest amplitude between clusters through the following formula: $\alpha_j > \bar{\alpha} + \omega S_{\alpha}$, where j = (1, 2, …, n) is the number of clusters; α_j is the correspondence joint point to n − j + 1 clusters; $\bar{\alpha}$ and S_{α} are the mean and the standard deviation of α'_j s, respectively, and ω is a constant equal to 1.25, as suggested by Milligan and Cooper (1985).

RESULTS AND DISCUSSION

The seeds of the corn hybrids used in this study had an initial water content between 11.8 and 13.0%. Corn hybrids had thousand seed weights ranging from 330 to 390 g. The emergence rate under control conditions was greater than 80% for all corn hybrids (Table 1), the minimum germination value required for the commercialization of corn seeds in Brazil. Under drought stress conditions, the minimum emergence rate was 54%.

The coefficient of variation (CV) values obtained in this experimental study were less than 10% for all morphological traits of corn plants (Table 3), a value considered low for laboratory experiments with agricultural plants. According to Pimentel-Gomes (2009), the CV is a measure of dispersion or variability that allows conclusions to be drawn about the experimental precision of scientific research, and when the values are less than 10%, it indicates that the results of the experimental bioassay have excellent precision.

The emergence stress tolerance index under drought stress conditions ranged from 60% to 100%, allowing differentiation of corn hybrids into four groups. The hybrids GALO VIP3, DKB 390 PRO4, FS 575 PWU, and GNZ 7757 VIP3 represented the group with the highest drought tolerance index, while the hybrids AS 1868 PRO4, B 2800 VYHR and AG 8088 PRO2 represented the group with the lowest drought tolerance index (Table 2).

Emergence stress tolerance index values lower than 100% indicate that drought stress inhibited the seed germination process, resulting in the lowest plant emergence rate for most corn hybrids (Table 2). The lower germination rate of seeds exposed to drought stress conditions has been commonly reported for corn crops. Kappes *et al*. (2010) reported that severe drought stress resulted in a reduction in the germination rate of four corn hybrids by up to 63% compared to the non-stressful control condition. Similarly, Queiroz *et al*. (2019) showed that the germination rate of corn under drought stress was reduced to 73% when compared to control conditions. Pias *et al*. (2017) also reported that drought stress inhibited the plant emergence rate of all four corn hybrids. The lower rate of plant emergence in drought conditions occurs because water stress results in a decrease in soil water potential, which impairs the water imbibition process and seed germination (Bewley *et al*., 2013). According to Taiz *et al*. (2017), the decrease in soil water potential results in a lower capacity for water absorption by seeds, which limits the germination and plant emergence process.

For the shoot length stress tolerance index, four groups of corn hybrids were separated, with values ranging from 40% to 91%. The LG 36745 PRO4, MG 545 PWU, AG 8700 PRO4, STINE 9075 VIP3, FS 575 PWU, and GNZ 7757 VIP3 are the hybrids belonging to the group with the highest drought tolerance index, while the hybrid AG 8088 PRO2 represented the group with the lowest drought tolerance index (Table 2).

Considering the root length stress tolerance index, three groups of corn hybrids were separated, with values ranging from 41% to 93%. The hybrids LG 36745 PRO4, MG 545 PWU, DKB 390 PRO4, and GNZ 7757 VIP3 represented the group with the highest drought tolerance index, while the hybrids ONÇA PRO2, AS 1868 PRO4, AG 8700 PRO4, DKB 360 PRO3, and AG 8088 PRO2 represented the group with the lowest drought tolerance index (Table 2). The total length stress tolerance index ranged from 45% to 92%, allowing differentiation of

Table 2 - Stress tolerance indices for plant emergence and growth traits of the 14 commercial corn (*Zea mays* L.) hybrids exposed to drought stress

Corn hybrid	Stress tolerance index (%)						
	E	SL	RL	TL	SDM	RDM	TDM
AG 8701 PRO4	88 b	65 b	70 b	68 b	72 b	62 b	70 b
LG 36745 PRO4	82 b	86 a	89 a	88 a	80 a	88 a	82 a
GALO VIP3	98 a	70 b	73 b	71 b	47 d	51 c	49 c
ONÇA PRO2	80 b	67 b	51 c	58 c	35 d	37 d	36 e
AS 1868 PRO4	65 d	61 c	51 c	57 c	56 c	53 c	54 c
MG 545 PWU	86 b	89 a	93 a	92 a	68 b	65 b	68 b
AG 8700 PRO4	84 b	86 a	54 c	72 b	59 c	55 c	57 c
B 2800 VYHR	66 d	65 b	70 b	68 b	46 d	44 d	45 d
DKB 390 PRO4	92 a	65 b	83 a	77 b	56 c	54 c	54 c
DKB 360 PRO3	74 c	56 c	55 c	56 c	40 d	43 d	41 d
STINE 9075 VIP3	80 b	86 a	67 b	80 b	59 c	53 c	54 c
FS 575 PWU	100 a	91 a	75 b	88 a	88 a	80 a	86 a
GNZ 7757 VIP3	96 a	87 a	89 a	89 a	80 a	71 b	77 a
AG 8088 PRO2	60 d	40 d	58 c	45 d	32 d	36 d	34 e
Mean	82	72	70	72	58	57	58
CV (%)	6.83	7.31	8.75	7.56	6.48	7.34	6.83

Mean followed by distinct letters on the column for the corn hybrids show significant differences by the Scott-Knott test at the 0.05 level of confidence. CV: coefficient of variation. **Abbreviations:** E: emergence; SL: shoot length; RL: root length; TL: total plant length; SDM: shoot dry matter; RDM: root dry matter; TDM: total plant dry matter

corn hybrids into four groups. The hybrids LG 36745 PRO4, MG 545 PWU, FS 575 PWU, and GNZ 7757 VIP3 represented the group with the highest drought tolerance index, while the AG 8088 PRO2 hybrid represented the group with the lowest drought tolerance index (Table 2).

In turn, for the shoot and root dry matter stress tolerance indexes under drought stress conditions, four groups of corn hybrids were separated. The hybrids LG 36745 PRO4, FS 575 PWU, and GNZ 7757 VIP3 represented the group with the highest drought tolerance index for shoot dry matter, while for root dry matter the hybrids LG 36745 PRO4 and FS 575 PWU represented the group with the highest drought tolerance index (Table 2). The total dry matter stress tolerance index ranged from 34% to 86%, allowing the differentiation of corn hybrids into five groups. The hybrids LG 36745 PRO4, FS 575 PWU, and GNZ 7757 VIP3 represented the group with the highest drought tolerance index, while the hybrids ONÇA PRO2 and AG 8088 PRO2 represented the group with the lowest drought tolerance index (Table 2).

Initial plant growth was inhibited by drought stress conditions for all corn hybrids (Table 2). The average value of the total length stress tolerance index was 72%, while the average value of the total dry matter stress tolerance index was 58%. These results show that both elongation and dry matter accumulation of corn plants were inhibited by drought stress. Queiroz *et al.* (2019) also showed that drought stress resulted in reduced length and dry matter accumulation in corn plants. This lower plant growth rate occurs because drought stress negatively impacts the primary cell growth parameters: wall extensibility and cell turgor (Taiz *et al*., 2017). Under drought stress, plant growth is affected due to reduced water absorption by plants and lower cell turgor pressure (Walne *et al*., 2024). Indeed, Li *et al*. (2001) reported a plant growth rate of 27.8 mm day^{-1} under non-stressful control conditions, whereas under drought conditions this growth rate was only 16.1 mm day^{-1}.

According to Silva *et al*. (2007), one of the first processes affected in response to decreased soil water availability is cell expansion, highly dependent process turgidity of the plants. As a result of these effects, plant dry matter production is reduced (Tabela 2). The lower accumulation of dry matter in the aerial part of plants exposed to drought conditions occurs due to a decrease in the rate of allocation of photoassimilates in the leaves and stems (Walne *et al*., 2024), which consists in plant response to water stress aimed at reduction of transpiration rate and optimization of water use. Drought stress has commonly limited the growth of several crops, such as soybeans (Cabral *et al*., 2022; Oliveira *et al*., 2023; Zuffo *et al*., 2020), sorghum (Queiroz *et al*., 2019), corn (Pandit *et al*., 2017; Queiroz *et al*., 2019; Walne *et al*., 2024) and cotton (Çelik, 2023; Zahid *et al*., 2021). Therefore, the response mechanisms of plants exposed to drought stress have become a crucial topic of environmental research in drought-prone regions.

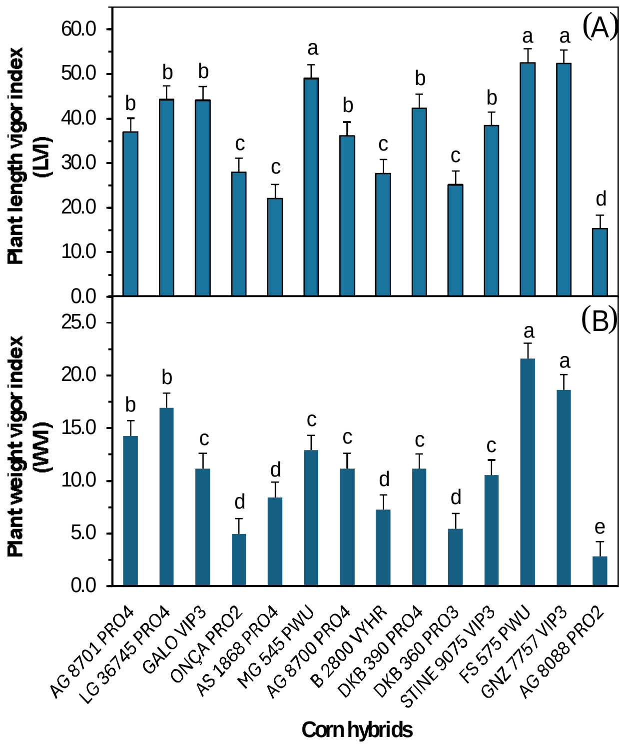
One of the main morphological responses of corn plants to drought stress is related to the characteristics of their root system. The roots are the first organ of the plant that is exposed to water stress, and they signal the rest of the plant under the occurrence of this stress (Taiz *et al*., 2017). After this signaling, the plant promotes other morphological, physiological, and metabolic changes to alleviate the adverse effects of drought and optimize plant growth under adverse conditions (Gopalakrishna *et al*., 2023; Kim; Lee, 2023; Walne *et al*., 2024). Root length growth and root system architecture have an important impact on water and nutrient absorption by plants (Tian; De Smet; Ding, 2014; Walne *et al*., 2024). In this study, the corn hybrids with the greatest drought tolerance are the genotypes that have the longest root length (Table 2 and Figure 3). For example, the hybrids LG 36745 PRO4, MG 545 PWU, FS 575 PWU, and GNZ 7757 VIP3 when exposed to drought stress had root lengths of 26, 28, 23, and 26 cm, respectively, and these were classified as drought tolerant (Supplementary Table S1). In turn, the hybrid AG 8088 PRO2 classified as drought sensitive had a root length of just 15 cm (Supplementary Table S1). Therefore, current plant breeding programs should select genotypes with longer roots for drought tolerance.

Similar results were reported by Walne *et al*. (2024), who reported that drought-tolerant corn hybrids (‘A6659’ and ‘D57VP51’) have greater root length growth when compared to the other 17 hybrids. These authors showed that the hybrids ‘A6659’ and ‘D57VP51’ exposed to drought stress had total root lengths of 6735 and 6302 cm, respectively, while the other corn hybrids had an average root length of 4820 ± 672 cm. Previous studies have also reported the importance of root length growth in inducing drought tolerance in soybean (Cabral *et al*., 2022; Oliveira *et al*., 2023) and cotton (Çelik, 2023) genotypes. These results may be due to the plant’s root tolerance mechanism, in which the plant increases the allocation of photoassimilates to the roots, to strengthen the root system and absorb more water in the soil profile. Under conditions of mild and moderate water stress, the photosynthetic products produced in the leaves are preferentially transported to the roots through vascular bundles (Çelik, 2023; Walne *et al*., 2024).

The length vigor index of corn plants under drought stress varied between 15.3 and 52.5 and was significantly higher for the hybrids MG 545 PWU, FS 575 PWU, and GNZ 7757 VIP3 (Figure 1A). In turn, the dry weight vigor index varied between 2.8 and 21.6 and was significantly higher for the corn hybrids FS 575 PWU and GNZ 7757 VIP3 (Figure 1B). Among the 14 corn genotypes, the hybrid AG 8088 PRO2 expressed the lowest value for the length and dry weight vigor indices (Figure 1).

The plant vigor index has been commonly used as a tolerance index to evaluate the impact of abiotic stresses on initial plant growth (Ashkan; Jalal, 2013; Oliveira *et al*., 2019). Seedling vigor is a measure of the level of damage that abiotic stresses cause to seed germination and the initial growth of seedlings (Bewley *et al*., 2013). The higher value of the length or weight vigor index observed in some corn hybrids is indicative of the greater tolerance of this genotype to drought stress conditions. In turn, the lower value of plant vigor indices obtained in the AG 8088 PRO2 hybrid indicates the greater susceptibility of this genotype to drought stress conditions.

Figure 1 - Plant length vigor index (A) and weight vigor index (B) of the 14 commercial corn hybrids (*Zea mays* L.) grown under drought stress conditions. Bars followed by distinct uppercase letters show significant differences by the Scott-Knott test at the 0.05 level of confidence. Data refer to mean values (n = 4) ± mean standard error



Identifying drought-tolerant or drought-sensitive corn hybrids based on a single stress tolerance index is not an easy task and can often lead to erroneous information (Table 2). Therefore, the differentiation of hybrids into different degrees of drought tolerance must be carried out considering all stress tolerance indices. Considering all drought stress tolerance indices, corn hybrids LG 36745 PRO4, MG 545 PWU, FS 575 PWU and GNZ 7757 VIP3 expressed the best average classification of the ranking method and, therefore, these hybrids were classified as drought tolerant. In turn, the hybrids ONÇA PRO2, AS 1868 PRO4, DKB 360 PRO3, and AG 8088 PRO2 received the highest scores in the ranking method and were then classified as susceptible to drought stress (Table 3).

Multivariate hierarchical clustering analysis of the 14 corn hybrids based on all drought tolerance indices classified the hybrids into four groups (Figure 2). The first group was represented by the corn hybrid with the lowest drought tolerance indexes and, therefore, was considered the group most sensitive to the negative effects of drought stress. The second group represented the corn hybrids with the highest drought tolerance indices and was therefore considered the most drought-tolerant group. In turn, the third and fourth groups represented hybrids with intermediate values of drought tolerance indices, and, therefore, corn hybrids belonging to these groups were classified as moderately sensitive and moderately tolerant to drought stress, respectively. Given the above, the corn hybrids FS 575 PWU, GNZ 7757 VIP3, LG 36745 PRO4, and MG 545 PWU were identified as the most tolerant to drought stress, while the hybrid AG 8088 PRO2 was classified as the most sensitive to drought (Figure 2).

In summary, the two multivariate analysis methods (ranking method and hierarchical grouping method) grouped the corn hybrids FS 575 PWU, GNZ 7757 VIP3, LG 36745 PRO4, and MG 545 PWU as tolerant to drought stress (Table 2, Figures 2 and 3). Therefore, these hybrids can be used as source material in developing drought-tolerant cultivars. Also, the tolerant hybrids will perform best under rainfed environments prone to early-season drought. This information is extremely important for Brazilian corn producers since this crop is widely grown in the Cerrado region, and in this region in many situations, farmers sow corn under inadequate soil moisture conditions to promote proper plant stand establishment in the field. Çakir (2004) showed that the occurrence of drought stress at the beginning of the vegetative growth stage results in poor plant stand in the field, which limits the grain yield of the crop.

In turn, the hybrid AG 8088 PRO2 was classified as sensitive to drought stress by the two multivariate analysis methods (Table 2, Figures 2 and 3), while the ranking method also classified the hybrids ONÇA PRO2,

Table 3 - Rank, rank mean ($\bar{R}$), and standard deviation of ranks (SDR) of drought tolerance indices of 14 commercial corn (*Zea mays* L.) hybrids

Corn hybrid	Stress tolerance index (%)							$\bar{R}$ ± SDR	Tolerance level†
	E	SL	RL	TL	SDM	RDM	TDM		
AG 8701 PRO4	5	10	7	9	4	5	4	6.3 ± 2.0	MT
LG 36745 PRO4	8	5	3	4	3	1	2	3.7 ± 1.7	T
GALO VIP3	2	7	6	8	10	9	10	7.4 ± 2.1	MT
ONÇA PRO2	10	8	13	11	13	13	13	11.6 ± 1.6	S
AS 1868 PRO4	13	12	14	12	9	9	9	11.1 ± 1.8	S
MG 545 PWU	6	2	1	1	5	4	5	3.4 ± 1.8	T
AG 8700 PRO4	7	4	12	7	7	6	6	7.0 ± 1.4	MT
B 2800 VYHR	12	11	8	10	11	11	11	10.6 ± 0.9	MS
DKB 390 PRO4	4	9	4	6	8	7	7	6.4 ± 1.5	MT
DKB 360 PRO3	11	13	11	13	12	12	12	12.0 ± 0.6	S
STINE 9075 VIP3	9	6	9	5	6	8	8	7.3 ± 1.4	MT
FS 575 PWU	1	1	5	3	1	2	1	2.0 ± 1.1	T
GNZ 7757 VIP3	3	3	2	2	2	3	3	2.6 ± 0.5	T
AG 8088 PRO2	14	14	10	14	14	14	14	13.4 ± 1.0	S

† T, refers to a drought-tolerant hybrid, having mean rank ($\bar{R}$) score of 1 to 4.2; MT, moderately tolerant hybrid with mean rank score of 4.3 to 7.5; MS, moderately sensitive hybrid with mean rank score of 7.6 to 10.7; and S, drought-sensitive hybrid with mean rank score of 10.8 to 14. **Abbreviations:** E: emergence; SL: shoot length; RL: root length; TL, total plant length; SDM: shoot dry matter; RDM: root dry matter; TDM: total plant dry matter

AS 1868 PRO4 and DKB 360 PRO3 as susceptible to drought stress (Table 2 and Figure 3). Though plants are sensitive to drought stress throughout the life cycle, the early plant growth stage is the foundation for higher yield potential (Vennam *et al*., 2023). Therefore, when corn is sown in regions with a high probability of drought or in soils with low water availability, these hybrids should not be recommended for cultivation.

Figure 2 - Dendrogram of the hierarchical cluster analysis of the 14 corn hybrids (*Zea mays* L) using the Euclidean distance and the unweighted pair group method with arithmetic mean (UPGMA) based on the stress tolerance indices of the plant emergence and growth traits (E, SL, RL, TL, SDM, RDM, and TDM)

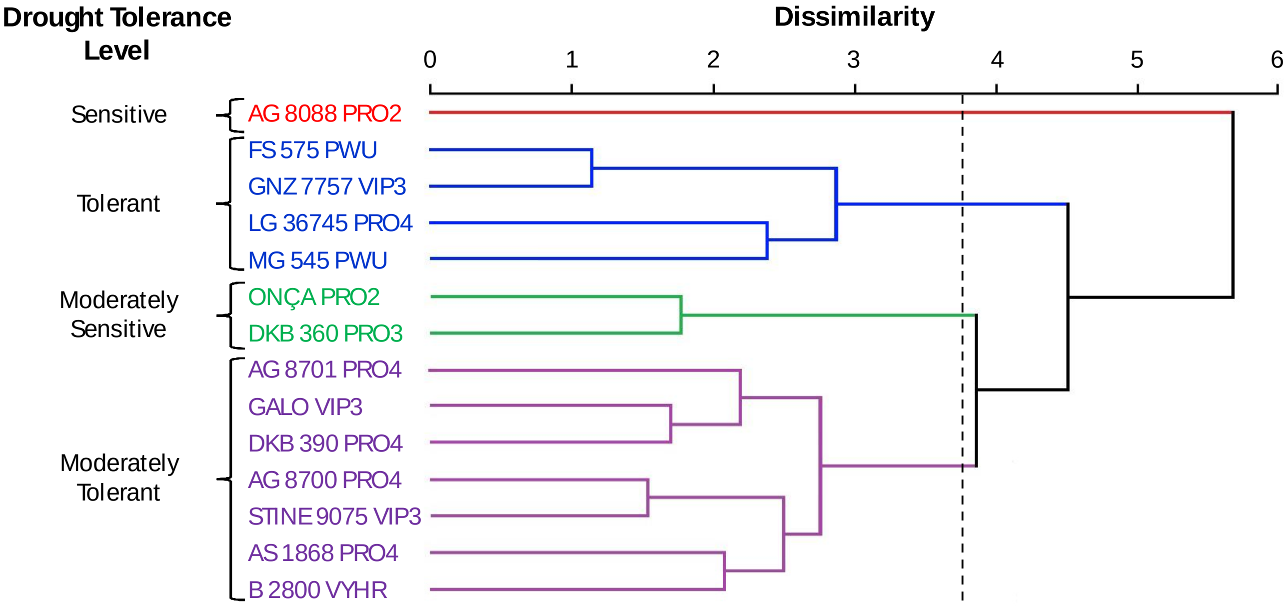


Figure 3 - Plants of the 14 corn hybrids (*Zea mays* L.) after 28 days of exposure to drought stress. T, MT, MS, and S indicate tolerant, moderately tolerant, moderately sensitive, and drought-sensitive corn hybrids, respectively, classified by the ranking or UPGMA methods

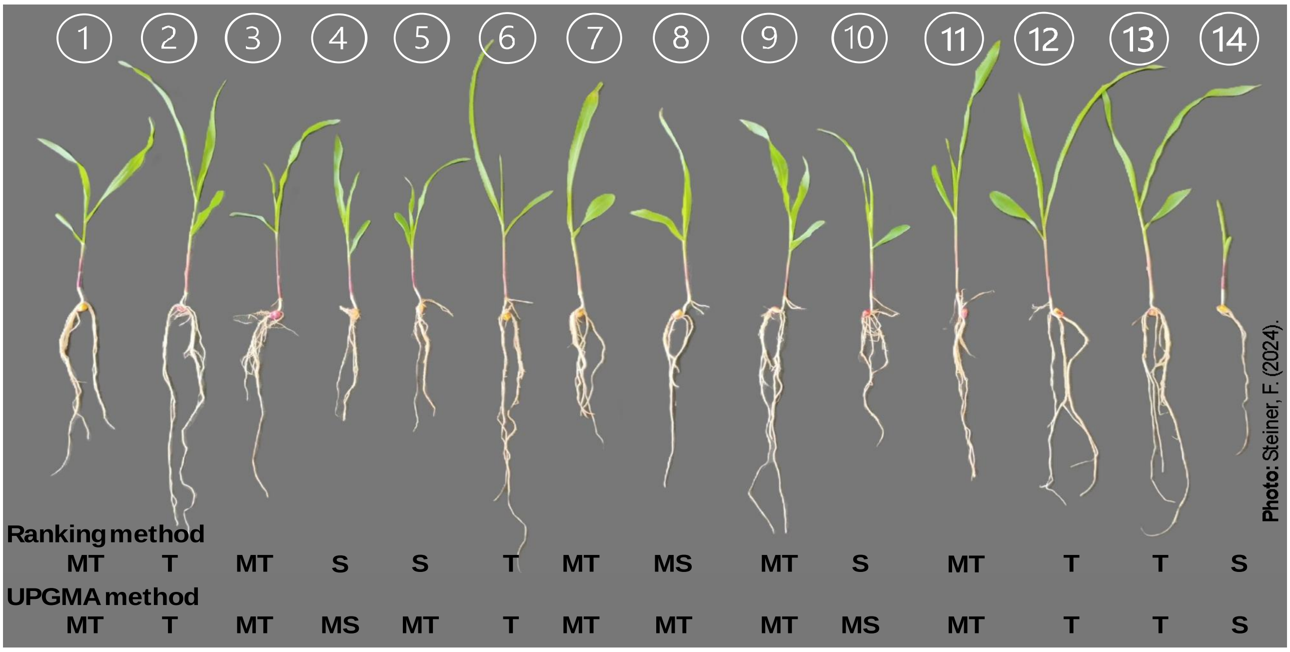


Photo source: Authors, Legend: 1-AG 8701 PRO4; 2-LG 36745 PRO4; 3-GALO VIP3; 4-ONÇA PRO2; 5-AS 1868 PRO4; 6-MG 545 PWU; 7-AG 8700 PRO4; 8-B 2800 VYHR; 9-DKB 390 PRO4; 10-DKB 360 PRO3; 11-STINE 9075 VIP3; 12-FS 575 PWU; 13-GNZ 7757 VIP3; 14-AG 8088 PRO2

The use of tolerant hybrids in rainfed conditions can improve the initial vigor of plants in the field and ensure excellent grain yield levels of the crop (Gopalakrishna *et al*., 2023; Vennam *et al*., 2023). Greater plant vigor results in increased photosynthetic rate and dry matter production, which results in rapid canopy closure, preventing soil water evaporation and improving root system development (Walne *et al*., 2024). These morphophysiological traits can improve water and nutrient uptake and maintain plant water and metabolic balance (Taiz *et al*., 2017; Vennam *et al*., 2023). Thus, the use of drought-tolerant hybrids during the early growth stage of plants can promote food security around the world by improving corn grain yield.

CONCLUSIONS

The corn hybrids FS 575 PWU, GNZ 7757 VIP3, LG 36745 PRO4, and MG 545 PWU have greater tolerance to drought stress and are the most suitable genotypes to be grown in conditions of low soil water availability;

The AG 8088 PRO2 corn hybrid has greater susceptibility to drought stress and should not be recommended for cultivation in conditions of reduced soil water availability.

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SUPPLEMENTARY MATERIALS

The following supporting information can be downloaded at: https://1drv.ms/b/s!Alz3pLwc2VDcgvhfWB9x8owMNYoknA?e=62bQAn. Table S1: Average morphological traits of the 14 corn hybrids (*Zea mays* L.) exposed to drought stress for 28 days.

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