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Can potassium fertilization alleviate the adverse effects of drought stress on soybean plants?

Adubação potássica pode aliviar os efeitos adversos do estresse hídrico nas plantas de soja?

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ABSTRACT: The adequate amounts of potassium (K) fertilizer application may play an essential role in the growth and tolerance of plants against the drought stress. In this study we investigate the effectiveness of potassium fertilization on the growth and tolerance of soybean plants [*Glycine max* (L.) Merrill.] to drought stress. Treatments were arranged in a randomized block design in a 2 × 3 factorial: two potassium fertilizer levels [40 mg kg^{-1} of K (low) or 160 mg kg^{-1} of K (high)] and three irrigation regimes [100% of pot capacity - PC (well watered control), 50% of PC (moderate stress) and 25% of PC (severe stress)] with four replicates. Leaf relative water content, cell membrane stability, plant growth, and morphophysiological indexes were recorded after 18 days of exposure to drought stress. The appropriate supply of potassium fertilizer improved leaf membrane stability and minimized the water loss from leaf tissue of soybean plants exposed to drought stress. The adverse effects of drought on leaf abscission and pod abortion rate could be mitigated by adequate K supply. The appropriate supply of potassium fertilizer alleviates the negative effects of drought stress and maintain shoot growth and the water status soybean plants, and therefore, the proper management of potassium fertilization may confer greater drought tolerance.

Keywords: *Glycine max*. Osmotic solutes. Potassium fertilizer. Relative water content. Water restriction.

RESUMO: A aplicação de quantidades adequadas de fertilizante potássico pode ter um papel essencial no crescimento e na tolerância das plantas quando expostas às condições de restrição hídrica. Neste estudo foi avaliada a eficácia da adubação potássica no crescimento e na tolerância das plantas de soja [*Glycine max* (L.) Merrill.] à deficiência hídrica. Os tratamentos foram dispostos em um delineamento de blocos casualizados em um esquema fatorial 2 × 3, constituído por dois níveis de adubação potássica [40 mg kg^{-1} de K (nível baixo) e 160 mg kg^{-1} de K (nível alto)] e por três regimes de irrigação [100% da capacidade de vaso - CV (controle), 50% da CV (estresse moderado) e 25% da CV (estresse severo)] com quatro repetições. O conteúdo relativo de água, a estabilidade da membrana celular, o crescimento das plantas e os índices morfofisiológicos das plantas de soja foram mensurados após 18 dias de exposição à restrição hídrica. A aplicação adequada de fertilizante potássico melhorou a estabilidade da membrana celular das folhas e minimizou a perda de água do tecido foliar das plantas de soja expostas às condições de restrição hídrica. Os efeitos adversos da restrição hídrica sobre a taxa de abscisão foliar e de aborto de flores e vagens podem ser amenizados pela aplicação adequada de K. A adequada aplicação de fertilizante potássico alivia os efeitos negativos da restrição hídrica e mantém o status hídrico das plantas e o crescimento da parte aérea da soja e, portanto, o adequado manejo da adubação potássica pode conferir maior tolerância à seca.

Palavras-chave: Conteúdo relativo de água. Fertilizante potássico. *Glycine max*. Restrição hídrica. Solutos osmóticos.

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INTRODUCTION

Soybean [*Glycine max* (L.) Merrill.] is one of the most important oilseed crops of the world. Brazil is one of the largest producers and exporters of soybean worldwide, with a planted area of 36.2 million hectares and production of 117.6 million tons in the 2018/2019 growing season (CONAB, 2019). However, drought is one of the most critical environmental factors that limit plant growth and grain yield of the soybean crop in Brazil and other areas of the world. The decrease in relation to the maximum yield potential of the crop (i.e., yield under ideal conditions) associated with water deficit can reach 70% (MERTZ-HENNING *et al*., 2018). Therefore, a high priority should be given to minimizing the detrimental effects of water restriction.

Drought results in the reduction of stomatal conductance and transpiration and photosynthetic rates (KRON; SOUZA; RIBEIRO, 2008, XU; ZHOU; SHIMIZU, 2010, VIEIRA *et al*., 2017), and may lead to changes in the root growth, initiation and expansion of leaf and reproductive structures rates (GRAY *et al*., 2016). Also, drought stress alters the activity of the nitrogen and carbon metabolism enzymes, as well as cause changes in the antioxidant levels (ZOZ *et al*., 2013, MANTOVANI *et al*., 2015). The first response to drought stress is a reduction in leaf area and plant growth rate, which leads plants to reduce their transpiration rate, with the attempt to increase water use efficiency (WUE) (XU; ZHOU; SHIMIZU, 2010). Plant response to drought includes morphological and biochemical changes and later as water stress becomes more severe occurs functional damage and loss of plant parts (SANGTARASH, 2010). However, these responses depend on several factors such as developmental stage, severity, stress duration and cultivar genetics.

Plants have developed a wide range of adaptive and/or resistance mechanisms to maintain productivity and ensure survival under drought stress conditions. To maintain higher tissue water content, plant cells can perform the osmotic adjustment, through the accumulation of several compatible solute/osmolytes like inorganic ions, organic acids, and carbohydrates, as well as free amino acids (BASU *et al*., 2016). This solute accumulation in the plant cells in response to water stress helps in maintaining the cell turgor and, therefore, constitutes a drought tolerance mechanism (WANG *et al*., 2013, BASU *et al*., 2016). Under conditions of drought stress, the osmotic adjustment has been implicated in maintaining stomatal conductance, photosynthesis, leaf water status, and plant growth rate (BAHRAMI-RADB; HAJIBOLAND, 2017).

Among the inorganic ions, potassium (K^+) has been cited as the main osmolyte that plays a significant role in osmotic adjustment. The accumulation of K^+ ions helps in protecting the plants from detrimental effects of drought stress not only by osmotic adjustment but also by detoxification of reactive oxygen species (ROS), stomatal regulation, protection of cell membrane integrity, and higher rates of photosynthesis (Wang *et al*., 2013). Furthermore, K is also essential for the translocation of photoassimilates in root growth (Hasanuzzaman et al. 2018). Therefore, adequate amounts of K fertilizer application may play an important role in the growth and resistance of plants against drought stress.

Indeed, Bahrami-Radb and Hajiboland (2017) showed that the stomatal regulation was improved upon K fertilizer application, which maintained the carbohydrate synthesis and, thus, enhancing the growth of tobacco (*Nicotiana rustica* L.) plants under drought stress. Zahoor *et al.* (2017) demonstrated that the K application improved osmotic adjustment and increased the N metabolism free amino acid, and sugars content in cotton (*Gossypium hirsutum* L.) plants under drought stress. Samar-Raza *et al.* (2013) reported that the application of K in wheat plants (*Triticum aestivun* L.) under drought stress enhanced tolerance of wheat by reducing toxic sodium uptake and improving the photosynthetic rate of plants. Zain *et al.* (2014) reported that application of K fertilizer not only increased shoot dry mass and leaf area but also improved the osmolytes synthesis in rice plants (*Oryza sativa* L.) under drought stress. Zhang *et al.* (2014) also showed that the K fertilization in maize (*Zea mays* L.) conferred water stress tolerance. However, the effect of potassium fertilization on the soybean tolerance to water deficit are still incipient and inconclusive (CATUCHI *et al.* 2012).

This study aimed to investigate the effectiveness of potassium fertilization on the growth and tolerance of soybean plants [*Glycine max* (L.) Merrill.] to drought stress.

2 MATERIAL AND METHODS

2.1 LOCATION AND ENVIRONMENTAL CONDITIONS

The experiment was conducted in a greenhouse in Cassilândia, MS, Brazil (19º05'20'' S, 51º48'24'' W, and altitude of 510 m), from November 2017 to January 2018. The environmental conditions during the experiment were: mean air temperature of 26.8 ºC during the day and 23.4 ºC during the night, average air relative humidity of 72% (±5%) and midday photosynthetic photon flux density of 982 μmol m^{-2} s^{-1} (±238 μmol m^{-2} s^{-1}).

The soil used in the experiment was a sandy Red-Yellow Latosol (Typic Hapludox), collected from a Cerrado area, with 200 g kg^{-1} of clay, 60 g kg^{-1} of silt and 740 g kg^{-1} of sand; pH in $CaCl_2$ 5.9; P (Mehlich-1) = 32 mg dm^{-3}; K (Mehlich-1) = 85 mg dm^{-3}; Al^{3+}, Ca^{2+}, Mg^{2+}, $H^+ + Al^{3+}$ = 0.0, 3.7, 1.6, 2.6 cmol$_c$ dm^{-3}, respectively; CEC = 8.1 cmol$_c$ dm^{-3}; base saturation = 68%; and organic matter = 20 g kg^{-1}. The field capacity, or its equivalent for soils in pots, the "pot capacity", was measured under free-draining conditions using the decrease rate of water content of 0.1 g kg^{-1} day^{-1} as previously recommended by Casaroli and Lier (2008), and the soil moisture content at pot capacity (PC) was 252 g kg^{-1}.

The soil was then placed in 12-L plastic pots and fertilized with 20 mg kg^{-1} of N (urea), 250 mg kg^{-1} of P (simple superphosphate), 30 mg dm^{-3} of S (gypsum), 2 mg kg^{-1} of Cu (copper sulfate), 2 mg kg^{-1} of Zn (zinc sulfate), and 0.5 mg kg^{-1} of Mo (ammonium molybdate). Fertilizer rates were incorporated into the entire soil volume of the pots at 5 days before soybean sowing. Each plastic pot was filled with 14 kg (±10 dm^3) of air-dried soil and sieved in a 4 mm mesh.

2.2 EXPERIMENTAL DESIGN AND TREATMENTS

The experimental was arranged in a randomized block design, using two potassium levels [40 mg kg^{-1} of K (low level) or 160 mg kg^{-1} of K (high level)] and three levels of drought stress [100% of pot capacity – PC (control), 50% of PC (moderate stress) and 25% of PC (severe stress)], considering a factorial arrangement (2 × 3) with four replicates. The K levels as potassium chloride (60% of K_2O) were divided into two applications at 5 and 20 days after soybean sowing.

A total of 48 pots were used – 8 pots per treatment. Four replicates were used for destructive samplings, including leaf area (LA) and dry matter partitioning between plant organs after 18 days of drought stress, which started after the flowering stage of soybean. The other four pots were used for the measurement of leaf relative water content and electrolyte leakage from cells during the 18 days of drought stress and after 3 days' recovery of plants in well-watered conditions.

2.3 CULTIVAR, EXPERIMENTAL CONDUCTION, AND IRRIGATION

The soybean seeds were previously inoculated with *Bradyrhizobium japonicum*, using the commercial liquid inoculant Simbiose Nod Soja® (Simbiose: Biological Agrotechnology) containing SEMIA 5079 and SEMIA 5080 strains (minimum concentration of 7.2×10^9 viable cells mL^{-1}), at a rate of 4 mL kg^{-1} of seed. Six seeds from cultivar 5D 615 RR were sown in plastic pots and, at seven days after emergence, seedlings were thinned down to two plants per pot. Until the flowering stage, the soil water content was maintained at pot capacity (252 g kg^{-1}) with daily irrigations. Posteriorly, the water restriction was established for 18 days, between R2 development stages (full flowering) and R5 (beginning of grain filling), with irrigation control performed by the gravimetric method (CATUCHI *et al.*, 2012). In addition to the control of irrigation replacement, soil water levels were monitored daily at 9:00 and 15:00 h using a digital thermo-hygrometer (Soil Moisture Sensor – 5TM, Decagon Devices, Inc., Pullman, WA, USA). After the period of exposure to drought stress, the plants were rehydrated under well-watered conditions for three days. In a previous trial, a three-day period was sufficient for the full recovery of soybean plants subjected to severe drought stress.

2.4 RELATIVE WATER CONTENT (RWC) AND MEMBRANE STABILITY INDEX (MSI)

The water status of the plants was determined by the leaf relative water content (RWC) at 1, 3, 6, 9, 12, 15 and 18 days after starting the drought stress and at 3 days after recovery. The RWC was calculated according to the following formula: RWC (%) = $[(FW - DW)/(TW - DW)] \times 100$. Twenty leaf discs of 6 mm in diameter were collected at 5:00 h a.m. (pre-dawn) and weighed immediately for the determination of fresh weight (FW). For measurement of turgid weight (TW), leaf disks were submerged for 6 h in distilled water at 25 °C, after that, they were blotted dry gently on a paper towel and weighed. Samples were then oven-dried at 75 °C for 24 h and weighed to determine the dry weight (DW).

Leaf membrane stability index (MSI) was assessed after 18 days of drought stress and 3-d recovery, as described by Lutts, Kinet and Bouharmont (1996). Twenty leaf discs of 8.5 mm diameter were thoroughly washed in distilled water, placed in closed tubes containing 30 mL of deionized water and incubated at 25 °C in a water bath for 6 h. Then the electrical conductivity of the solution was recorded using a Sanxin® model MP521 pH/EC meter (C_1). Subsequently, the same samples were placed in a boiling water bath (100 °C) for 1 h, and their electrical conductivity (C_2) was also recorded after equilibration at 25 °C. The membrane stability index was calculated according to the following formula: MSI (%) = $[1 - (C_1/C_2)] \times 100$.

2.5 MEASUREMENT OF GROWTH AND DRY MATTER PARTITIONING

After the 18th day of exposure to drought stress, the plants were harvested and, then the plant height, number of leaves, number of pods, leaf area, root volume, and dry matter of the plant parts were measured. The plants were separated into leaves, stem, pods, and roots, oven-dried at 65 ºC for three days, and then weighed. The shoot dry matter was obtained from the sum of the dry matter of the stem, leaves, and pods. The Total dry matter was obtained from the sum of all plant parts (stem, leaves, pods, and roots). The results were expressed in grams per plant (g $plant^{-1}$). To determine the ratio shoot: root dry weight (S:R), shoot dry matter obtained was divided by the root dry matter. The leaf and pod abscission was determined as the percentage of leaves or pods that shed with a gentle touch during the 18 days of exposure to drought stress.

Leaf area (LA) was determined following the methodology described by Benincasa (2003) by weighing leaf discs. Fifteen discs were detached from the basal, median, and apical leaves. Total LA was estimated using the following equation: $LA = [(A_D \times TDM_L)/DM_D]$, where A_D is the known area of the detached leaf discs, TDM_L is the total dry matter of the leaves, and DM_D is the dry matter of the detached leaf discs. Root volume (RV, cm^3 $plant^{-1}$) was determined by water displacement using a calibrated cylinder of 250 mL.

Leaf area ratio (LAR), specific leaf area (SLA) and leaf weight ratio (LWR) were determined from the leaf area values (LA) expressed in dm^2 per plant, total dry matter of the plant (TDM) and leaf dry matter (LDM), both expressed in g per plant, using the following equations, according to Benincasa (2003): [LAR (dm^2 g^{-1}) = LA / TDM], [SLA (dm^2 g^{-1}) = LA / LDM] and [LWR (g g^{-1}) = LDM / TDM].

2.6 STATISTICAL ANALYSIS

The Kolmogorov-Smirnov test previously tested the data normality at 5% of significance, and then data were submitted to analysis of variance (ANOVA), and the averages for potassium level and drought stress were compared by the Tukey test, at the 5% level of significance. The analyses were performed using Sisvar® (version 5.6) software for Windows (Statistical Analysis Software, UFLA, Lavras, MG, BRA).

3 RESULTS AND DISCUSSION

3.1 RELATIVE WATER CONTENT

The level of K fertilizer applied did not significantly affect ($p > 0.05$) the leaf relative water content (RWC) until the 6th day of exposure to drought stress (Table 1). After the 9th day of drought, the plants fertilized with a high level of K had the higher leaf RWC. These results indicate that the addition of high amounts of K fertilizer minimized the loss of leaf water content during drought stress. This increase in RWC was due to K improving plant osmotic adjustment under drought stress conditions. The application of K fertilizer in rice plants (*Oryza sativa* L.) improved the osmolytes synthesis under drought conditions, which induced an increase in the leaf water content (ZAIN *et al*., 2014). The K fertilization in cotton plants (*Gossypium hirsutum* L.) also improved osmotic adjustment under drought conditions (ZAHOOR *et al*., 2017). Bahrami-Radb and Hajiboland (2017) also showed that tobacco plants (*Nicotiana rustica* L.) fertilized with K fertilizer exhibited higher RWC in the leaf tissue and greater stomatal regulation and carbohydrates synthesis in drought conditions.

The RWC of the control plants under well-watered conditions remained constant, with values reaching from 92 to 94% (Table 1). Drought stress caused a decrease in the RWC of soybean plants with values reaching 81% and 76% (moderate stress) and 72% and 51% (severe stress) at 6 and 18 days, respectively. The decrease of 19% (moderate stress) and 46% (severe stress) in the leaf RWC at 18 days resulted in decreased turgescence, chlorosis mainly in the old leaves, and high leaf abscission rate. After rehydration, RWC reached values similar to the control plants, restoring the leaf turgescence. Drought stress adversely affects many physiological processes in plants, and the decrease in leaf RWC is one of the first adverse effects of water stress (PINHEIRO; CHAVES, 2011).

Table 1. Effects of K fertilizer level and drought stress level on the leaf relative water content (RWC) of soybean [*Glycine max* (L.) Merrill., cv. 5D 615RR] at pre-dawn during 18 days of exposure to drought stress and after 3 days of recovery of the plants under well-watered conditions

Causes of variation	Days after the imposition of drought stress							
	1st	3rd	6th	9th	12th	15th	18th	21th (†)
Potassium fertilizer level	Leaf relative water content (RWC)							
Low	91 a	84 a	79 a	73 b	73 b	70 b	70 b	91 a
High	92 a	87 a	82 a	78 a	80 a	78 a	77 a	94 a
Drought stress level								
Control (100% PC)	94 a	93 a	93 a	92 a	94 a	92 a	94 a	93 a
Moderate stress (50% PC)	91 a	87 b	81 b	77 b	78 b	77 b	76 b	91 a
Severe stress (25% PC)	90 a	79 c	72 c	61 c	58 c	53 c	51 c	94 a
CV (%)	5.34	6.52	6.88	7.43	8.81	7.94	7.24	6.34

Mean followed by distinct letters for the factors K fertilizer level and drought stress show significant differences (Tukey test, $p \leq 0.05$). CV: coefficient of variation. PC: pot capacity. (†) Relative water content (RWC) measured after three days of recovery of the plants under well-watered conditions.

3.2 CELL MEMBRANE STABILITY

The level of K fertilization significantly affects ($p < 0.05$) the leaf membrane stability index (MSI) of soybean plants (Figure 1). Plants fertilized with a high K level had higher MSI after 18 days of drought stress when exposed to drought stress. After 3 days of recovery, the leaf MSI was significantly greater in plants fertilized with a high K level only under severe drought stress. These results indicate that the application of high K level reduced damage to cell membranes caused by drought. A similar result was reported by Wei *et al*. (2013), who showed that the adequate supply of K improved the cell membrane integrity of wheat plants under drought conditions.

Similarly, Soleimanzadeh *et al*. (2010) reported that addition of high K level significantly increased electrolyte leakage and cellular membrane permeability in sunflower plants (*Helianthus annuus* L.) under water shortage conditions, which indicates the role of K in mitigating oxidative stress. This improvement in the stability of plant cell membranes with the application of high K level indicates the role of K in mitigating oxidative stress, which increases the drought tolerance of plants. Under drought conditions, excess reactive oxygen species production in plants may exaggerate cellular lipid peroxidation, leading to an increase in the cellular membrane permeability, which is evidenced by increases in the electrolyte leakage (PINHEIRO; CHAVES, 2011, HASANUZZAMAN *et al*., 2018).

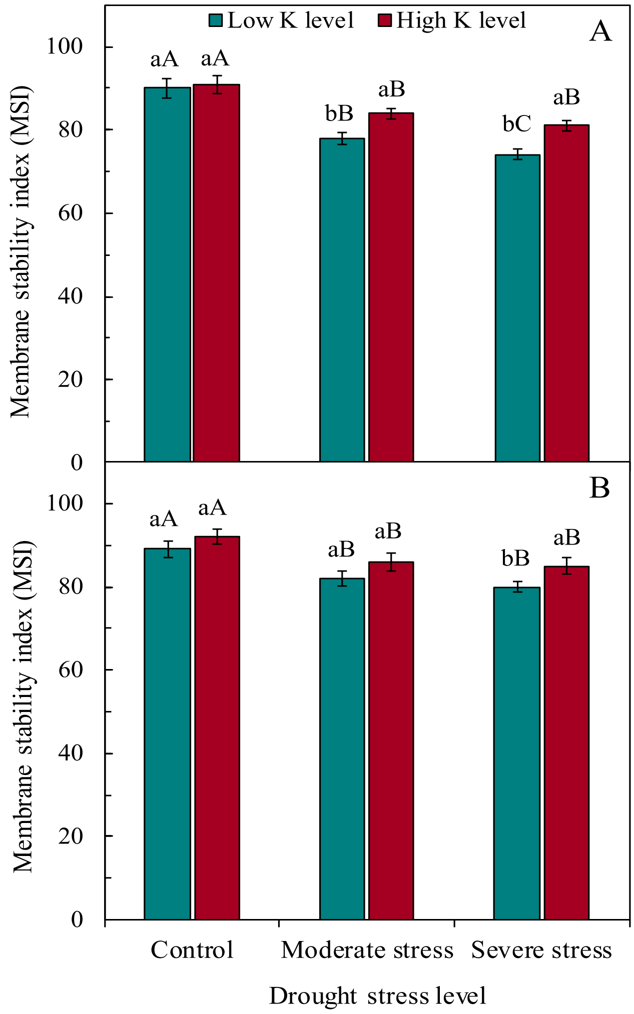

Figure 1. Effect of K fertilizer level and drought stress level on leaf membrane stability index (MSI) of soybean [*Glycine max* (L.) Merrill., cv. 5D 615RR] at pre dawn after 18 days of exposure to drought stress (A) and after 3 days of recovery of the plants under well-watered conditions (B). Bars followed by the same lower-case letters, between the K levels or same upper-case letters, for the drought stress levels are not significantly different by Tukey test at the 0.05 of significance. Data refer to mean values ($n = 4$) ± mean standard error.

Drought stress led to a significant decrease in membrane stability index (Figure 1). The lower stability of leaf membranes observed in soybean plants under water shortage conditions indicates that cell membrane injury was increased. Under drought stress conditions, plants produce reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2), superoxide anion radicals (O_2^-), and hydroxyl radicals (OH^-). These ROS react with proteins, lipids, and deoxyribonucleic acid causing oxidative damage and impairing the cell membrane permeability (Vurukonda et al. 2016). The damage caused by ROS on cell integrity is due to the lipid peroxidation of cellular membranes (PINHEIRO; CHAVES, 2011).

3.3 PLANT GROWTH

In well watered control conditions, the leaf area, shoot dry matter and total dry matter was significantly higher in the plants fertilized with high level of K, while the plant height, leaf area, root dry matter, root volume was not significantly affected ($p > 0.05$) by the addition of K fertilizer levels (Figure 2). Under moderate drought stress, the plant height, shoot dry matter, and total dry matter was significantly greater with the application of the high level of K fertilizer, whereas under severe drought stress, the plants fertilized with high K level had higher shoot dry matter, total dry matter, and root volume.

In general, the results indicate that dry matter production of shoots and total under drought stress conditions was optimized by the application of the high level of K. It suggests that the adverse effects of drought on the shoot growth of soybean plants were mitigated by the adequate supply of K. Zain *et al*. (2014) reported that sufficient supply of K improved the shoot dry matter production of the rice plants under dry conditions. O K plays a role in cell turgor maintenance, osmotic adjustment, and aquaporin function under drought conditions, which improves the growth of plants (WANG *et al*., 2013, ZAHOOR *et al*., 2017).

The leaf area and dry matter production were drastically inhibited with drought stress (Figure 2). Plants exposed to severe drought stress had an average reduction of leaf area, shoot dry matter, total dry matter, and root volume of 34%, 40%, 32%, and 18%, respectively, when compared to plants under well watered conditions.

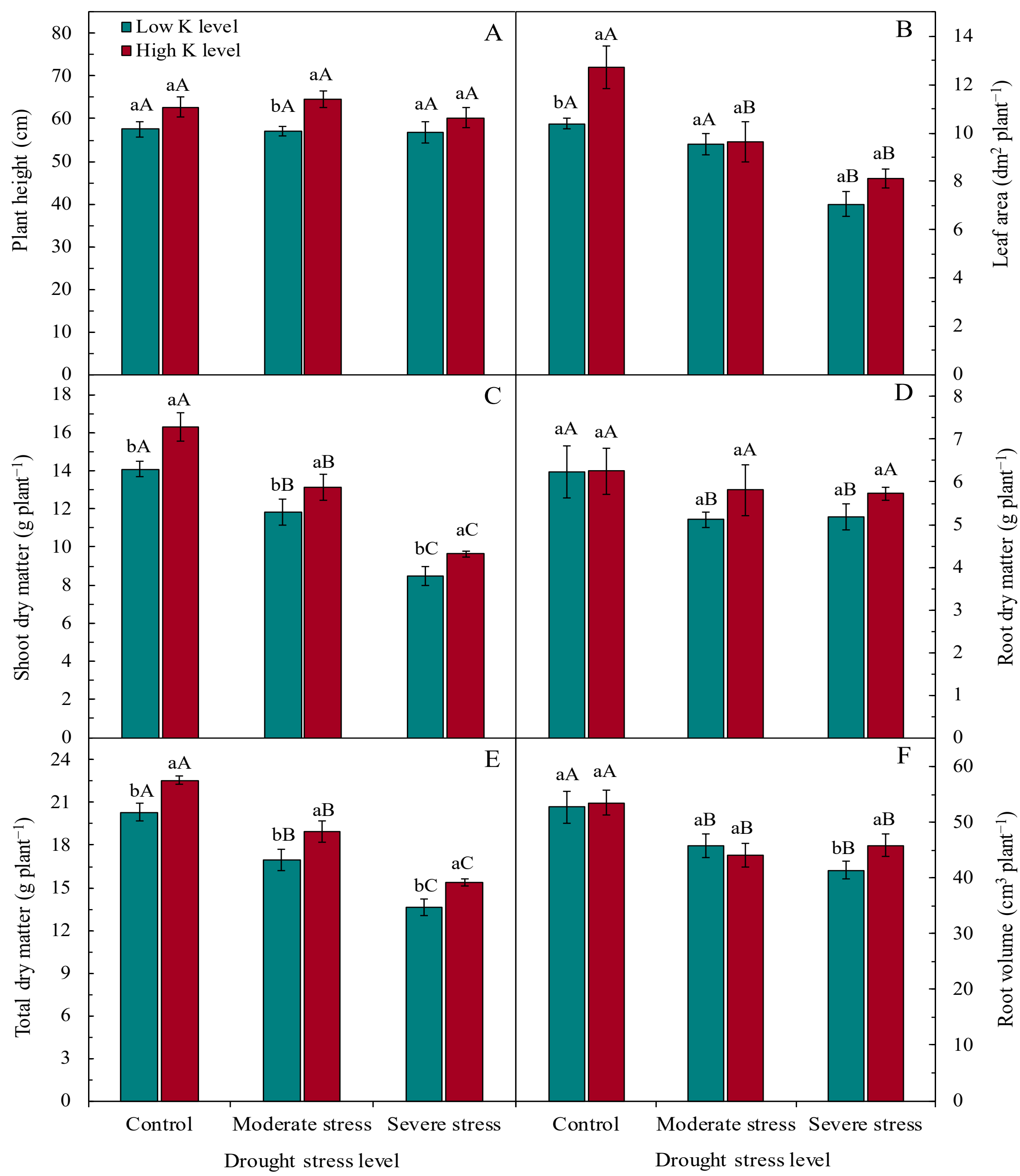

Figure 2. Effect of K fertilizer level on plant height (A), leaf area (B), shoot dry matter (C), root dry matter (D), total dry matter (E) and root volume (F) from soybean plants under well watered conditions (control) or plants exposed to 50% pot capacity (moderate drought stress) and 25% pot capacity (severe drought stress) for a period of 18 days. Bars followed by the same lower-case letters, between the K levels or same upper-case letters, for the drought stress levels are not significantly different by Tukey test at the 0.05 of significance. Data refer to mean values (n = 4) ± mean standard error.

These results report the typical response of plants to drought stress usually reported in the literature (ZOZ *et al*., 2013, NAVEED *et al*., 2014, CURÁ *et al*., 2017). One of the first processes affected in response to decreased soil water availability is cell expansion, highly dependent process turgidity of the plants. However, with the advancement of drought, other physiological processes are affected, with direct effects on the photoassimilates accumulated by the plant, reduction in the carbon assimilation rate, and relative growth rate (PINHEIRO; CHAVES, 2011). As a result of these effects, there is a reduction in leaf area and dry matter production. The reduction of leaf area and leaf production occurs as a defense reaction of plants to drought, reducing the transpiration rate and, therefore, the water loss to the atmosphere.

The application of high K level reduced the percentage of leaf abscission under severe drought stress but had no effect under moderate stress (Figure 3a). These results report that an adequate supply of K fertilizer was efficient in minimizing the negative effects of drought on leaf abscission only under severe stress. This induction of drought tolerance to soybean plants may be due to the ability of K in regulating the osmotic adjustment (WANG *et al*., 2013, ZAHOOR *et al*., 2017), and maintain the cell turgor (WANG *et al*., 2013, ZAHOOR *et al*., 2017), which reduces leaf abscission. Plants under drought stress have a series of physiological, morphological, and biochemical changes, which include loss of leaf turgor, and increase foliar senescence and leaf abscission (PINHEIRO, CHAVES, 2011).

The application of high K level reduced the percentage of pod abortion under moderate and severe drought stress (Figure 3b). Drought stress decreases the carbon availability and changes the dry matter partitioning between different parts of the plant. When water restriction occurs during the reproductive stage of the plant, the lower availability of carbon may limit the dry matter partition to the reproductive organs, resulting in flower dropping and pod abortion. However, pod abortion can be attenuated with an adequate supply of K fertilizer. The K application improves the osmolytes synthesis under drought conditions, resulting in higher leaf water content, greater stomatal regulation, and carbohydrate synthesis (ZAIN *et al*., 2014, BAHRAMI-RADB; HAJIBOLAND, 2017).

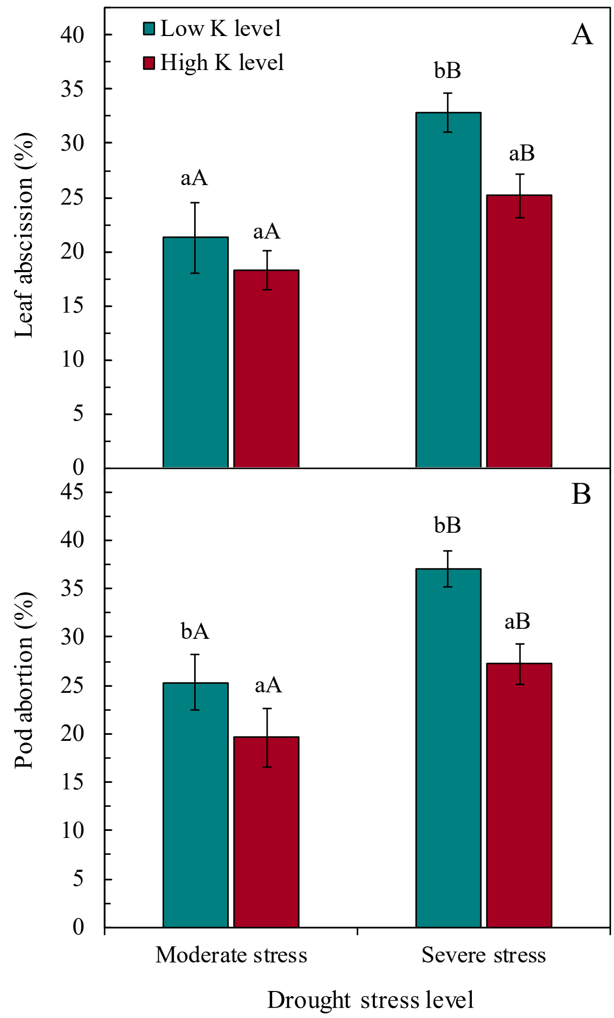

Figure 3. Effect of K fertilizer level on the leaf abscission (A) and pod abortion (B) from soybean plants exposed to 50% pot capacity (moderate drought stress) and 25% pot capacity (severe drought stress) for 18 days. Bars followed by the same lower-case letters, between the K levels or same upper-case letters, for the drought stress levels are not significantly different by Tukey test at the 0.05 of significance. Data refer to mean values ($n = 4$) ± mean standard error.

The levels of K fertilizer applied did not affect significantly ($p > 0.05$) the shoot: root dry weight ratio, leaf area ratio (LAR), specific leaf area (SLA), and leaf weight ratio (LWR) of the soybean plants (Figure 4). The shoot: root ratio is one of several ratios, which give estimates of dry matter partitioning into roots and shoots, and it is a good indicator for drought stress effects on root and shoot dry matter (BOUTRAA *et al.*, 2010). The shoot to root ratio of soybean plants was reduced under severe stress conditions (Figure 4a). A decrease in the shoot to root ratio (i.e., an increase in the root system proportion) was expected to be a common response of plants to drought stress. Under water shortage conditions, root often grows thicker, deeper, and larger in response to drought (XU et al., 2015). Since plants acquire water through roots, any plasticity in root architecture also enables plants to respond to a water shortage condition (SANGTARASH, 2010, XU et al., 2015).

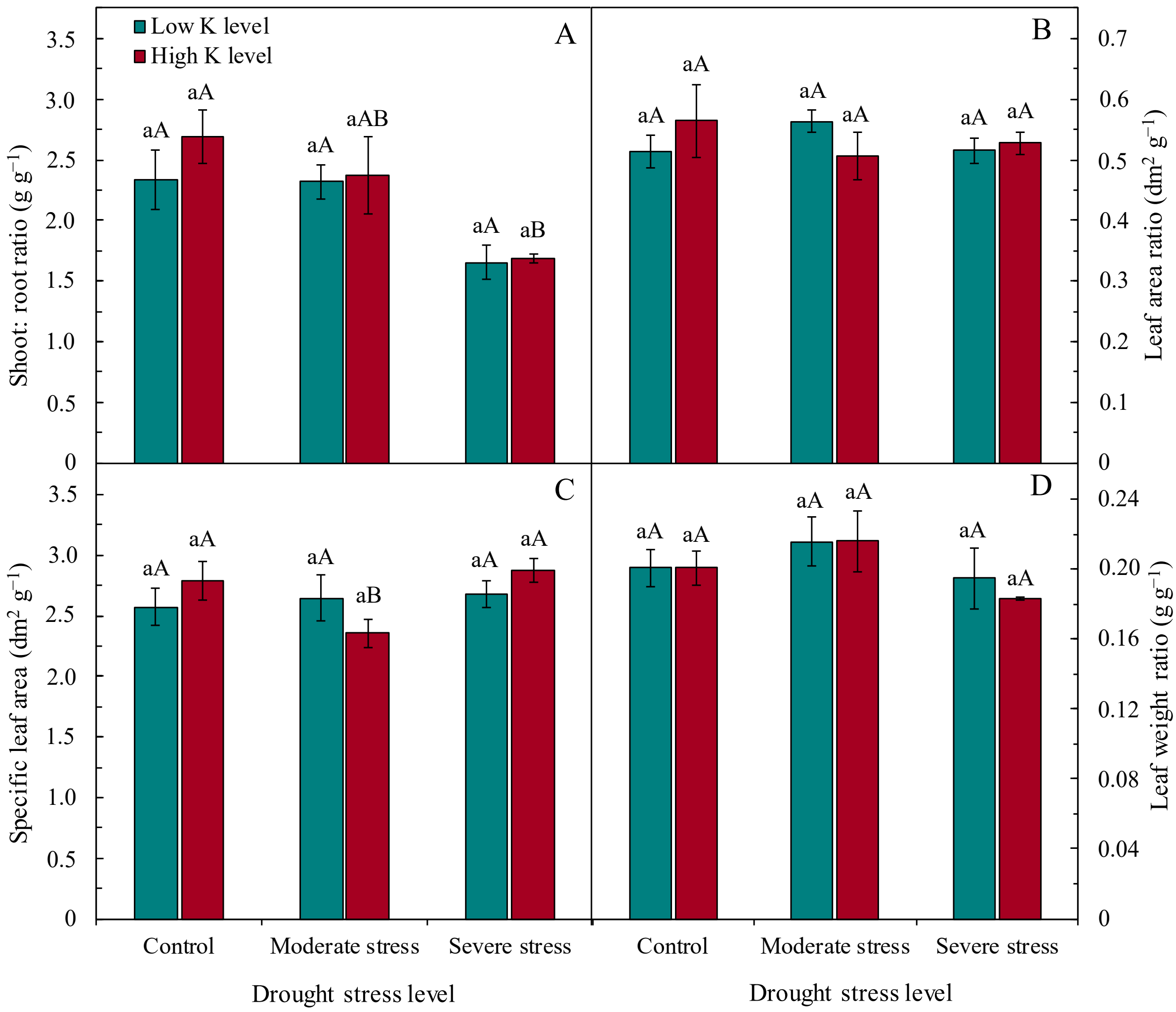

Figure 4. Effect of K fertilizer level on shoot: root dry weight ratio (A), leaf area ratio (B), specific leaf area (C) and leaf weight ratio (D) from soybean plants under well watered conditions (control) or plants exposed to 50% pot capacity (moderate drought stress) and 25% pot capacity (severe drought stress) for a period of 18 days. Bars followed by the same lower-case letters, between the K levels or same upper-case letters, for the drought stress levels are not significantly different by Tukey test at the 0.05 of significance. Data refer to mean values (n = 4) ± mean standard error.

Specific leaf area (SLA) is an essential morphological characteristic of the plant that determines the new leaf area to be deployed for each unit of dry matter produced and has been widely used as an indirect measure of leaf thickness (BENINCASA, 2003). Any storage of extra carbohydrate in the leaves, or any reallocation of biomass to thicker leaves, would tend to increase the leaf mass more than leaf area, thereby decreasing the SLA. In this study, the application of a high K level under moderate stress conditions resulted in the thickening of the leaves (i.e., lower specific leaf area) (Figure 4c). According to Wellstein *et al*. (2017), lower SLA is associated with enhanced water-use efficiency under water stress and, thus, can be seen as a strategy of phenotypic adjustment. The phenotypic adjustment is an important factor of short-term functional plant response to climatic extremes such as drought. However, these effects were not observed under severe stress conditions.

The leaf weight ratio (LWR) represents the fraction of dry mass not exported from leaves to the other organs of the plant (BENINCASA, 2003). In this study, K fertilizer levels and drought stress levels did not modify the allocation of photoassimilates to leaves, in detriment of the other organs of the plants.

In general, the results presented here demonstrate that a sufficient supply of K fertilizer can ameliorate the adverse effects and potentiate the growth of soybean plants under conditions of water restriction, making it an important tool in Brazil's soybean production systems. In addition to its nutritional effect for soybean plants, K can confer greater tolerance to drought stress, avoiding the increase in leaf membrane damages, maintaining plant growth, and minimizing the loss of leaf water content and leaf and pod abscission. Several studies have also reported improved drought tolerance of plants with adequate K supply in other crops, such as rice (ZAIN *et al*., 2014), cotton (ZAHOOR *et al*., 2017), maize (ZHANG *et al*., 2014), wheat (SAMAR-RAZA *et al*., 2013) and tobacco (BAHRAMI-RADB; HAJIBOLAND, 2017).

4 CONCLUSIONS

The appropriate supply of potassium fertilizer improved leaf membrane stability and minimized the water loss from leaf tissue of soybean plants exposed to drought stress.

The negative effects of drought on leaf abscission and pod abortion rate could be mitigated by adequate K supply.

The appropriate supply of potassium fertilizer alleviates the negative effects of drought stress and maintain shoot growth and the water status soybean plants, and therefore, the proper management of potassium fertilization may confer higher drought tolerance.

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