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Article

Tolerance of Different Cowpea Cultivars Subjected to Irrigation with Saline Waters

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RESUMO

Partindo do pressuposto de que a salinidade da água de irrigação influencia o crescimento e a produtividade das plantas de feijão-caupi, este estudo teve como objetivo avaliar o efeito dos níveis de salinidade da água de irrigação sobre as características morfológicas e produtivas de três cultivares de feijão-caupi. O experimento foi constituído por cinco níveis de salinidade da água de irrigação: (0,01; 1,41; 2,81; 4,21 e 5,61 dS m^{-1}), três cultivares (BRS Tumucumaque, BRS Guariba e BRS Imponente) e dois períodos de cultivo. O delineamento experimental adotado foi em blocos casualizados em esquema de parcelas subsubdivididas com quatro repetições. Foram avaliados os seguintes parâmetros: diâmetro do caule (DC), altura da planta (AP), número de ramos laterais (NLP), comprimento da vagem (C), número de grãos por vagem (NGP), peso de dez vagens (PV), número de vagens por planta (PVP), peso de 100 grãos (PGP) e produtividade de grãos. Os dados foram submetidos à análise de variância aplicando-se o teste F a 5% de probabilidade. Foi realizada análise de regressão para o fator quantitativo. Houve efeito significativo da interação entre os fatores em todas as variáveis analisadas. O aumento da salinidade da água de irrigação reduz o desempenho morfológico e a produtividade das cultivares de feijão-caupi BRS Tumucumaque, BRS Guariba e BRS Imponente. Entretanto, a cultivar BRS Tumucumaque foi a mais tolerante aos efeitos negativos decorrentes do aumento da salinidade da água de irrigação.
Palavras-chave: vigna unguiculata, estresse salino, brs tumucumaque, brs guariba, brs imponente.

ABSTRACT

Assuming that irrigation water salinity influences the growth and yield of cowpea plants, this study aimed to evaluate the effect of irrigation water salinity levels on the morphological and production traits of three cowpea cultivars. The experiment consisted of five salinity levels of irrigation water: (0.01, 1.41, 2.81, 4.21 and 5.61 dS m^{-1}), three cultivars (BRS Tumucumaque, BRS Guariba, and BRS Imponente) and two periods of cultivation. A completely randomized block design was adopted in a split-split plot arrangement with four replications. The following parameters were evaluated: stem diameter (SD), plant height (PH), number of lateral branches (NLB), pod length (PL), number of grains per pod (NGP), ten-pod weight (TPW), number of pods per plant (NPP), 100-grain weight (GW) and grain yield. The data were subjected to analysis of variance by applying the F-test at 5% probability. Regression analysis was performed for the quantitative factor. There was a significant effect of the interaction between factors on all variables analyzed. The increase in irrigation water salinity reduces the morphological performance and yield of the cowpea cultivars BRS Tumucumaque, BRS Guariba, and BRS Imponente. However, the cultivar BRS Tumucumaque was the most tolerant to the negative effects resulting from increased irrigation water salinity.
Keywords: vigna unguiculata, salt stress, brs tumucumaque, brs guariba, brs imponente.

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Introduction

Agricultural irrigation is one of the technologies that most contributes to increasing food production. However, this practice should be used rationally since the different soil uses and managements, allied to high temperatures, low rainfall rates, and high salt contents of irrigation water, typical of Northeastern Brazil, have caused soil salinization (Pessoa et al. 2022).

Climate changes tend to aggravate this problem, and projections made until the year 2100 are not encouraging, indicating an increase in soil and water salinity in various regions of the planet (Hassani et al. 2021). Besides that, there may also occur an increase in the water or osmotic potential, ionic stress, and oxidative cell stress, primarily due to the overproduction of reactive oxygen species (ROS) (Tavares et al. 2021; Gogna et al. 2020; Sheikh-Mohamadi et al. 2022). These factors disturb basic physiological processes such as nutrient uptake and photosynthesis, affecting plant growth and development (Hossain 2019; Challabathula et al. 2022).

For that reason, the soil salinity level should always be lower than the level harmful to cultivated plants. In Northeastern Brazil, the water sources used for irrigation often show salt concentrations ranging from 1 to 30 $mmol_c\ L^{-1}$, corresponding to the electrical conductivity range of 0.1 to 3.0 dS m^{-1} (Holanda & Amorim 1997). In this scenario, cowpea [*Vigna unguiculata* (L.) Walp.] is a crop of moderate tolerance to irrigation water salinity, high temperatures, and water stress. This species is mainly grown in tropical and subtropical regions where salinity is a limiting factor for production (Sadeghipour 2017).

The value of 3.3 dS m^{-1} is considered the threshold salinity level for cowpea (Ayers; Westcot 1999), although this number can vary from cultivar to cultivar. Moreover, some cowpea cultivars are known to have developed to adapt to certain abiotic adverse conditions such as high salinity, temperatures, and radiation levels (Praxedes et al. 2022). However, although the incidence of these factors can be considered altogether, studying these factors in isolation is also necessary, especially with regard to the performance of cowpea cultivars in regions with soil salinization problems.

Therefore, assuming that irrigation water salinity influences the growth and yield of cowpea plants, this study aimed to evaluate the effect of irrigation water salinity levels on the morphological and production traits of three cowpea cultivars.

Materials and Methods

Establishment and conduction of the experiment

As an experimental strategy, two irrigated experiments were conducted at the experimental area of the School Farm Alvorada do Gurguéia – FEAG, belonging to the Federal University of Piauí (UFPI) in the municipality of Alvorada do Gurguéia-PI, located at 08º 22' 28" S, 43º 51' 34" W, and at an elevation of 229 meters a.s.l. The first experiment was conducted from August 20 to October 30, 2017, and the second experiment was conducted from August 25 to November 4, 2018. According to Thornthwaite and Mather, the climate of the region is classified as C1, i.e., a dry, sub-humid, megathermal climate, with a small water surplus (Andrade Júnior et al. 2004).

According to the Brazilian Soil Classification System (Santos et al., 2013), the soil of the experimental area is classified as a "Neossolo Quartzarênico Órtico Típico". Soil chemical characterization (Table 1) was performed in both cultivation years, and the area was split into sub-plots (3 x 6 m) in 2018. Then, three cowpea cultivars of the same commercial class and with similar maturation periods and sizes were chosen for this study. More details on the characterization and establishment of the experimental area can be found in Silva Júnior et al. (2021).

Table 1. Physico-chemical characteristics of the soil in the experimental area at Alvorada school farm (FEAG), before planting in the first year of cultivation. Alvorada do Gurguéia, PI. SB- Sum of Bases; CEC- Cation Exchange Capacity; ESP- Exchangeable Sodium Percentage; SOM- Soil Organic Matter; V- Base saturation; m- Aluminum saturation.

pH	**H+Al**	**Al**	**Ca**	**Mg**	**SB**	**CEC**	**ESP**	**SOM**
H_2O	**--------------------------- cmol$_c$ dm^{-3} -------------------------**						**%**	**g kg^{-1}**
5.8	1.05	0.00	1.36	0.10	1.46	2.52	0.00	5.5
P	**K**	**Na**	**V**	**m**	**Clay**	**Silt**		**Sand**
----------- mg dm^{-3} -----------			**-------%-------**		**---------------- g/kg ----------------**			
11.42	12.15	0.00	56.4	0.0	76	14		910

Source: Authors.

Experimental design

Five levels of electrical conductivity of irrigation water (EC) were studied: 0.01 (EC_0, well water that supplies the FEAG), 1.41 (EC_1), 2.81 (EC_2), 4.21 (EC_3), and 5.61 (EC_4) dS m^{-1}, corresponding to the main factor. In addition, three cowpea cultivars (C), BRS Tumucumaque (C_1), BRS Guariba (C_2), and BRS Imponente (C_3) constituted the secondary factor. Finally, two years of cultivation (YC) (2017 and 2018) were the tertiary factors. A completely randomized block design with a split-split plot arrangement and four replications was used in the experiment.

The pre-established EC levels were obtained by adding salt (NaCl) to irrigation water, considering the artificial salinity curve (Figure 1). First, the NaCl was diluted in 30 disposable 200 mL cups at concentrations ranging from 0.1 to 3.0 g NaCl L^{-1}, with an interval of 0.1 g L^{-1} between dilutions, and using a conductivity meter (model ION Con500) to read the EC. Then, the data were used to construct the equation employed to determine the NaCl content needed to obtain the EC of each level.

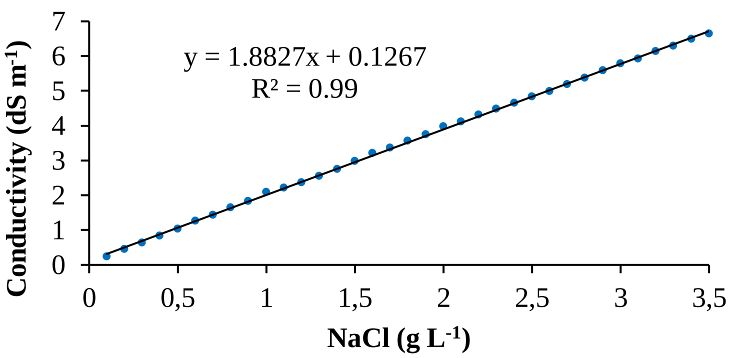

Figure 1. Artificial salinity curve. Alvorada do Gurguéia, PI. 2017. Source: Authors.

Since the EC is influenced by the environment, even with the exact mass of NaCl for each level defined by the equation, it was necessary to observe the EC behavior after the solutions were prepared by making, whenever necessary, adjustments in the mass values to initiate the experiments. The cowpea seeds provided by the Cowpea Breeding Program at Embrapa Meio-Norte were subjected to chemical treatment with fipronil + thiophanate methyl + pyraclostrobin at a proportion of 200 mL/100 kg of seeds to prevent the attack by soil pathogens and/or insects.

After the application of NaCl and before the second year of cultivation, the chemical characterization of the soil remained like that presented in Table 1. However, the concentration of Na and ESP increased with the higher soil electrical conductivity in the treatments, where there was a Na concentration of 2.90, 35.14, 61.45, 90.76 and 133.96 mg dm^{-3} and ESP of 0.40, 5.13, 8.11, 12.68 and 16.83 % for EC_0, EC_1, EC_2, EC_3 and EC_4, respectively.

Sowing was performed manually on August 20, 2017 (first cultivation year) and on August 25, 2018 (second cultivation year), by distributing two seeds per hole in order to achieve the pre-established planting density. The plants were thinned to one plant per hole ten days after sowing (DAS). During thinning, the plants were cut below the cotyledonary node to prevent them from resprouting and avoiding damage to the root system of the remaining plants. The salt stress treatments began at 15 DAS.

The crop management practices included cleaning the area and applying chemical products whenever necessary. No soil correctives and/or chemical or organic fertilization were performed during any of the periods, and the assay was conducted with a surface drip irrigation system. More details on irrigation and other crop management practices can be seen in Silva Júnior et al. (2021).

Before planting, the soil was irrigated until it achieved field capacity. Irrigation management was based on the reference evapotranspiration (ETo) and the crop coefficient (Kc). The Kc followed the recommendations for the different crop phenological stages (Bastos et al. 2008). Irrigation was performed daily by replenishing 100% of the crop evapotranspiration (ETc) during the cultivation cycle.

The irrigation depths were calculated using an electronic sheet where the daily ETo values were recorded, estimated by the Penman-Monteith method using climatic data (Figures 2 and 3) obtained by the automatic weather station of INMET located in the municipality of Alvorada do Gurguéia-PI, approximately 7 km from the experimental area.

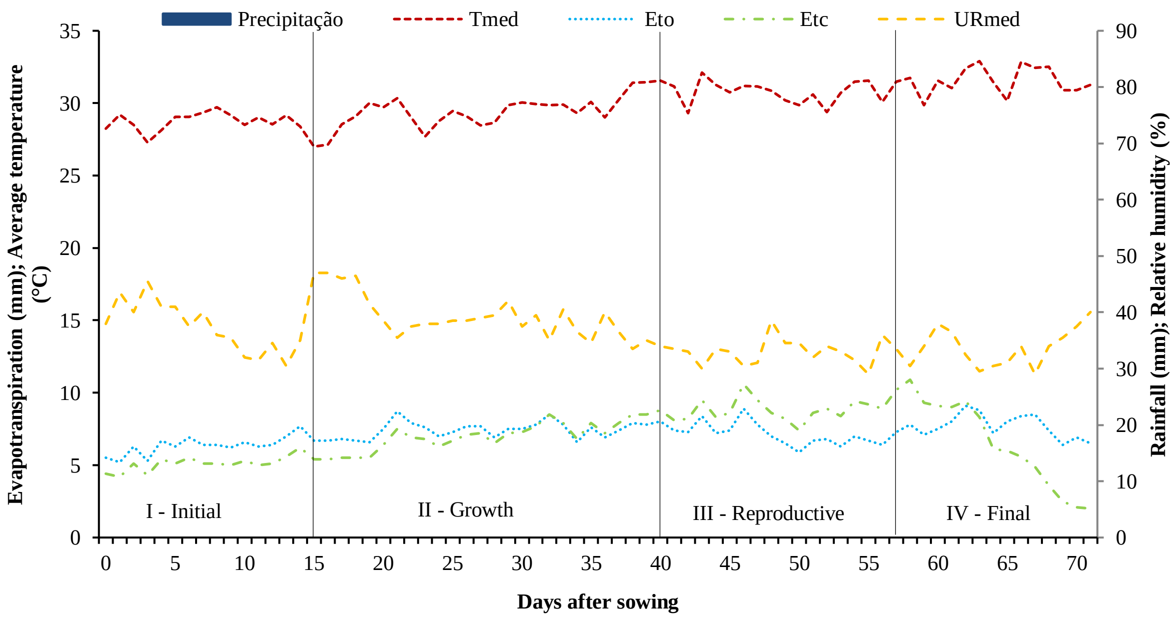

Figura 2. Average temperature (ATemp), average relative humidity (ARH), reference evapotranspiration (ETo), crop evapotranspiration (ETc) and rainfall. Alvorada do Gurguéia, PI. 2017. Source: National Institute of Meteorology-INMET.

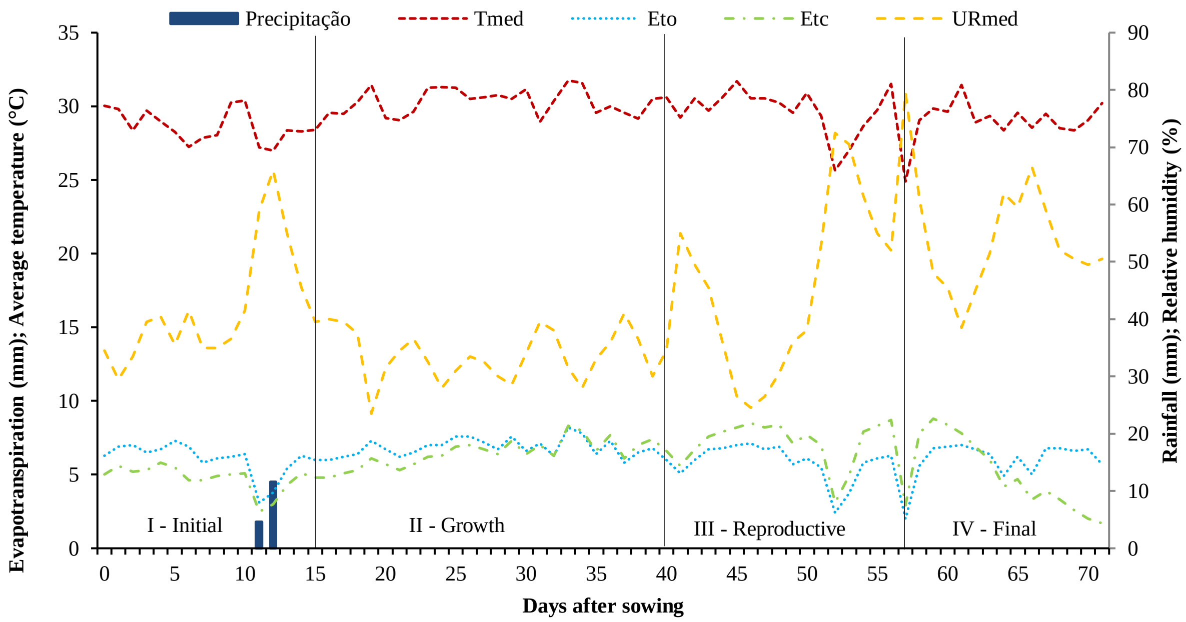

Figure 3. Average temperature (ATemp), average relative humidity (ARH), reference evapotranspiration (ETo), crop evapotranspiration (ETc) and rainfall. Alvorada do Gurguéia, PI. 2018. Source: National Institute of Meteorology-INMET.

The water volumes used in each treatment were stored in tanks with a capacity of 1,000 L before the beginning of each irrigation event, according to the volume to be applied at each treatment. The salts were weighed in a precision balance accurate to 0.1 g, dissolved in 20-L buckets, and then added to the water tanks according to the respective salinity levels, being well-mixed to ensure good homogenization. The EC was measured through daily readings using a portable conductivity meter to maintain greater control of the salinity levels of each treatment throughout each cultivation cycle. Salt stress began at 15 DAS.

Variables analyzed

The following variables were analyzed at 71 DAS: soil sodium content (Na^+ mg dm^{-3}); stem diameter (SD, as mm), measured with a digital caliper immediately before the cotyledonary node; plant height (PH, as cm), measured between the cotyledonary node and the apical bud; number of lateral branches (NLB); pod length (PL, as cm); number of grains per pod (NGP); number of pods per plant (NPP); 100-grain weight (100-GW as g); and grain yield, corresponding to the total grain production in the usable area of the subplot, transformed into kg ha^{-1}.

The SD, PH, NLB, and NPP are presented by means of four plants chosen randomly by per subplot. The NGP corresponds to the mean of ten pods chosen randomly in each subplot. The GW was obtained by considering the mean of three samples of 100 grains, per subplot, with approximately 13% moisture.

The chemical analyses performed to quantify the soil contents of Na^+ refer to 60 composite samples collected at a depth of 0-0.20 m in each subplot (cowpea cultivars) to evaluate the effect of the treatments (electrical conductivity of irrigation water – EC), after the first (October 2017) and second year of cultivation (November 2018). For the composite samples, three single samples were collected randomly from each subplot of each experimental block.

Then, the soil samples were air-dried, passed through a 2-mm sieve, and analyzed at the Soil Laboratory of the Campus Professora Cinobelina Elvas of the Federal University of Piaui - CPEC/UFPI, according to the methodology described in the Manual of Soil Analysis Methods (Teixeira et al., 2017). Na^+ was extracted using the Mehlich^{-1} solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}) and quantified by flame spectrophotometry.

Statistical analysis

The data were subjected to analysis of variance by applying the F-test at 5% probability to verify the effect (significant or not) of each factor and the interaction between them on the evaluated traits. For the qualitative factor, Tukey's test was applied at 5% probability using the statistical software SISVAR (Ferreira, 2014). The regression analysis was performed for the quantitative factor by choosing, between the linear and quadratic models, the best-fit model according to the level of significance and the highest coefficient of determination (R^2).

Results and Discussion

The soil sodium contents (Na^+) at the end of each cultivation cycle showed significant linear increases ($p<0.01$) in the interaction between irrigation water salinity and the years of cultivation when the EC increased from 0.01 to 5.61 dS m^{-1}, highlighting the effects of the treatments applied in each plot. In the second year of cultivation (2018), the mean increase corresponded to 14.5% in relation to the first year (2017) (Figure 4).

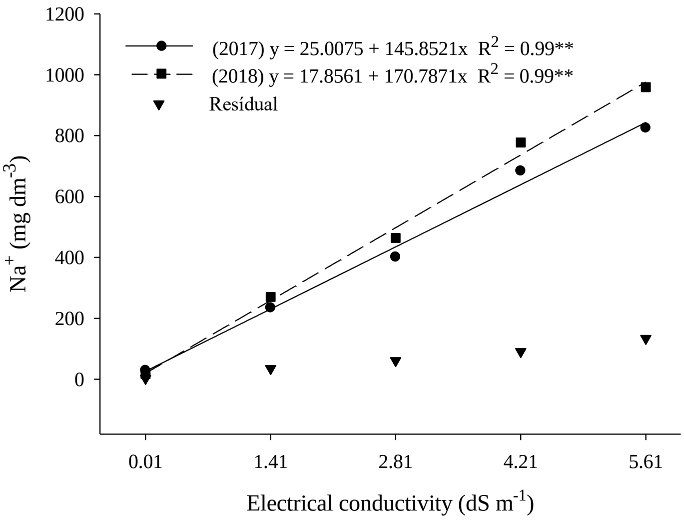

Figure 4. Soil sodium content (Na+) after the cultivation of three cowpea cultivars (BRS Tumucumaque, BRS Guariba, and BRS Imponente) under five electrical conductivity levels of irrigation water (EC) and two years of cultivation (2017 and 2018), and Na+ content before the second year of cultivation (residual). Alvorada do Gurguéia, PI. 2019. Source: Authors.

This higher sodium increase in the second year of cultivation is due to the residual Na^+ before the beginning of the second cultivation cycle (Figure 4). This residual appeared because the rainfall between the end of the first cycle and the beginning of the second year of cultivation was probably insufficient to leach all the Na^+ applied by irrigation.

Morphological variables

Regardless of the year, the increase in salinity caused an interaction between EC and AC, with significant linear reductions ($p<0.01$) for the stem diameter (SD) of the three studied cultivars (Figure 5A). On average, the mean reductions amounted to 21.1% in the first year (2017) and 23.5% in the second (2018). The three cultivars also showed significant linear reductions ($p<0.01$) for SD caused by the EC (Figure 5B). The cv. BRS Imponente was the most sensitive to salinity, showing the highest SD reduction (25.6%). In contrast, the cultivar BRS Guariba showed the lowest SD reduction (18.9%), highlighting its greater stability among the three cultivars to withstand the adverse effects caused by increased EC levels in the irrigation water (Figure 5B).

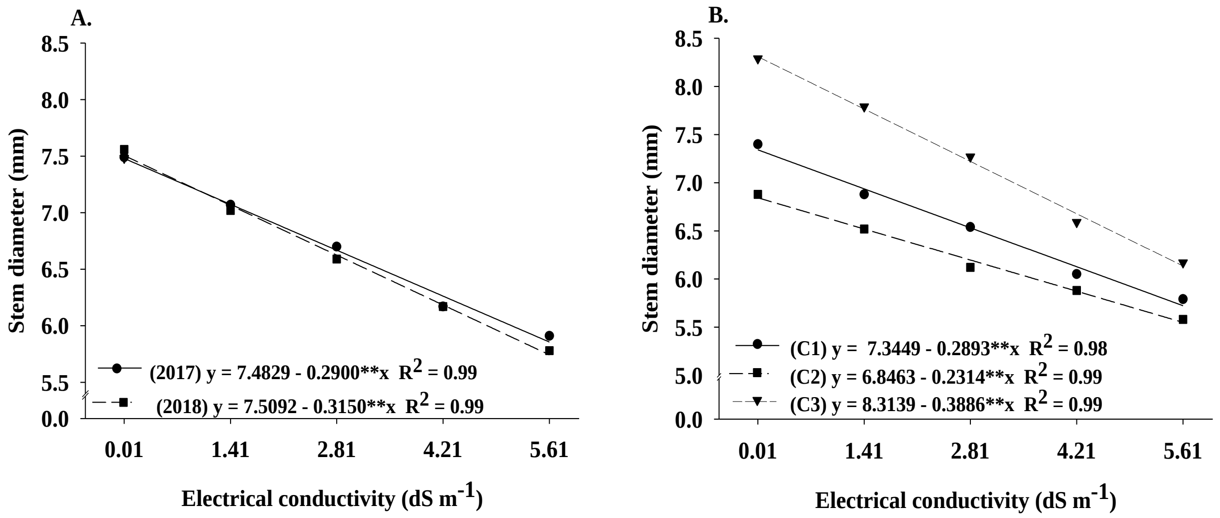

Figure 4. (A) Effects of the interaction between electrical conductivity x year of cultivation (2017-2018) and (B) electrical conductivity x cultivars on the stem diameter (SD) of cowpea plants 71 days after sowing (DAS). Cultivars: BRS Tumucumaque (C_1), BRS Guariba (C_2), and BRS Imponente (C_3). Alvorada do Gurguéia, 2019. Source: Authors.

Similar results were found by Andrade et al. (2013), who studied the cowpea cultivar 'Quarentinha' under plant nursery conditions. The authors observed a linear decline higher than 21.0 % in the stem diameter under salt stress 35 days after sowing. These results are similar to those of Aquino et al. (2017) regarding the linear reduction in response to increased irrigation water salinity. However, the reduction percentages of the first authors were higher since Aquino et al. (2017) found mean reductions of 9.0% in the SD at 35 DAS when the EC increased from 0.55 to 6.40 dS m^{-1}.

The reduction of SD can be associated with the different resistance levels shown by the cultivars when the EC increases. On the other hand, it should be noted that larger stem diameters can favor plant resistance to lodging (Xiang et al., 2019).

Plant height (PH) was also influenced by the EC x AC interaction. The three cultivars showed significant linear reductions with the increase in irrigation water salinity ($p<0.01$), with an average of 24.5% in 2017 and 25.4% in 2018 (Figure 6A). In the EC x C interaction, the three cultivars also showed significant linear reductions ($p<0.01$) for PH. The cv. BRS Tumucumaque was the most sensitive to the effects of salinity, showing the highest reduction (31.1%), whereas the cultivar BRS Imponente showed the lowest reduction (17.6%), thus highlighting its greater stability among the three cultivars to withstand the negative effects of increased salinity (Figure 6B).

Aquino et al. (2017) evaluated the morphophysiological responses of cowpea genotypes to irrigation water salinity levels ranging from 0.55 to 6.40 dS m^{-1} and observed significant linear reductions of 5.12 and 7.7% for SD at 25 and 35 DAS, respectively. The authors also observed that the negative effects were intensified by 50.7% when comparing the results at 25 and 35 DAS, indicating a cumulative negative effect, which can become more drastic in the reproductive stage. It is possible that the reductions in the SD and PH parameters could be due to the indirect effects caused by hindered water uptake, the toxicity of specific ions, the interference of ions with physiological processes, and ions resulting from the excessive accumulation of salt fixed at the uppermost soil layers over time under low leaching rates (Dias & Blanco 2010).

Furthermore, the lowest mean values observed for PH, especially in the cv. BRS Imponente, could be connected to the reduction in the osmotic and water potential of the soil resulting from the salt excess mentioned before. This scenario causes plants to activate morphological, anatomical, and biochemical defense mechanisms, thus providing larger amounts of photoassimilates to the roots, which are in direct contact with salts, consequently reducing shoot growth (Taiz & Zeiger 2013; Sogoni et al. 2021).

In a study by Win and Oo (2015), saline stress significantly reduced plant height, number of leaves and leaf area per plant, chlorophyll content, shoot length, root length and the biomass of all evaluated genotypes. In general, cowpea plants stressed with NaCl show a significant decrease in the total dry matter of leaves, stems, roots and total dry matter, regardless of the salinity level and cowpea genotype, mainly caused by the drastic decrease in photosynthesis liquid and stomatal conductance of cowpea genotypes (Miranda et al. 2021).

About the number of lateral branches (NLB), the three cultivars responded similarly to the increase in the EC of irrigation water, as indicated by the non-significant interaction in the two years of cultivation (Table 4). However, significant differences ($p<0.01$) were observed between cultivars, with the cv. BRS Imponente showing the highest NLB mean (0.57) and differing significantly ($p<0.05$) from the cultivars BRS Tumucumaque and BRS Guariba, both with a mean value of 0.26 (Figure 7).

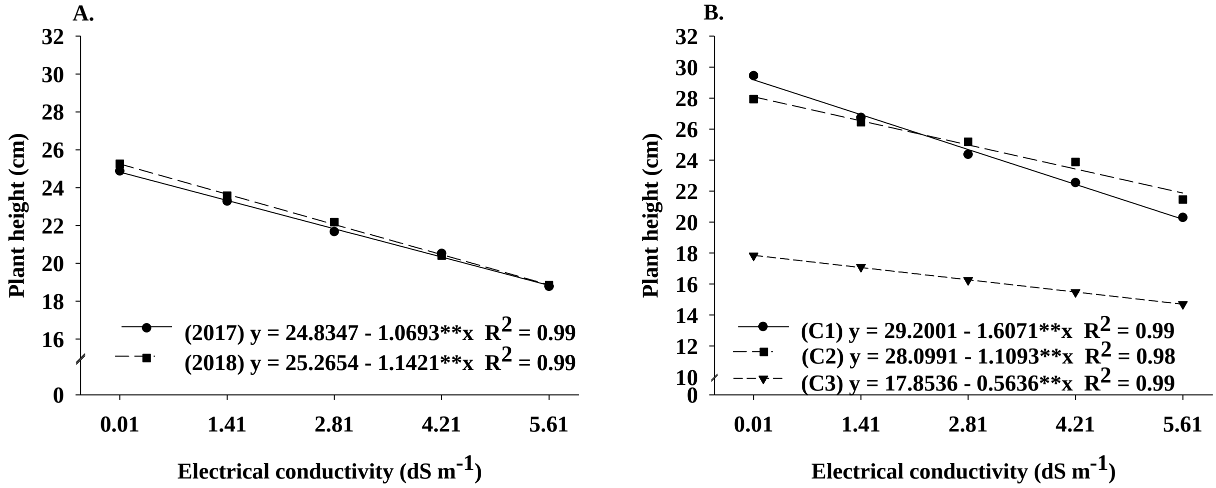

Figure 6. (A) Effects of the interaction between electrical conductivity x year of cultivation (2017-2018) and (B) electrical conductivity x cultivars on the plant height (PH) of cowpea plants 71 days after sowing (DAS). Cultivars: BRS Tumucumaque (C_1), BRS Guariba (C_2), and BRS Imponente (C_3). Alvorada do Gurguéia, 2019. Source: Authors.

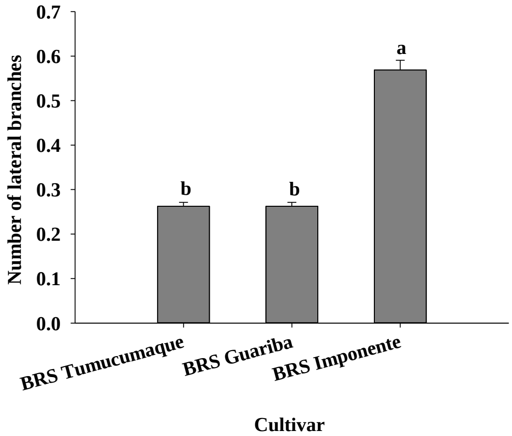

Figure 7. Number of lateral branches (NLB) 71 days after sowing (DAS) of three cowpea cultivars (BRS Tumucumaque (C1), BRS Guariba (C2), and BRS Imponente (C3)) subjected to five electrical conductivity levels of irrigation water (EC) in two years of cultivation (2017 and 2018). Data corresponds to the average of two years and all irrigation levels. Equal letters (in the columns) do not differ ($p>0.05$) by Tukey's test. Alvorada do Gurguéia, 2019. Source: Authors.

Salt stress tends to reduce the emission of reproductive branches and increase the abortion rate (Furtado et al. 2014). However, in general, the cultivar BRS Imponente reduced its growth and tended to invest in stem diameter and lateral branches as a possible morphological mechanism against the harmful effects of salinity. This reduced growth can be attributed to limitations in root water absorption due to the accumulation of salts in the soil solution, affecting processes such as cell expansion (Oliveira et al., 2024). A study by Aquino et al. (2017) observed that BRS Imponente had the largest stem diameter compared to other genotypes, indicating better stem structure.

Production variables

The analysis of variance showed a significant interaction ($p<0.05$) between the electrical conductivity of irrigation water (EC), the cultivars (C), and the year of cultivation (AC) for the ten-pod weight (PDV) and the ten-pod grain weight (PGDV) evaluated at 71 DAS, indicating that the cultivars respond differently to the increase in the EC levels of irrigation water. The CVs ranged from 1.13 to 10.6%, indicating good accuracy for the results obtained (Table 2).

With regard to the number of grains per pod (NGP), the increases in the EC of irrigation water promoted negative quadratic effects ($p<0.01$) in the EC x AC interaction. The maximum yields estimated for the NGP in the first (4.71) and second years of cultivation (5.67) were obtained at the electrical conductivity levels of 1.13 and 1.16 dS m^{-1} of irrigation water in each cultivation cycle, (2017) and 54.8% in the second year (2018) when the EC increased until the maximum level studied (5.61 dS m^{-1}), indicating a generally negative effect in the responses to the increased EC levels of irrigation water (Figure 9A).

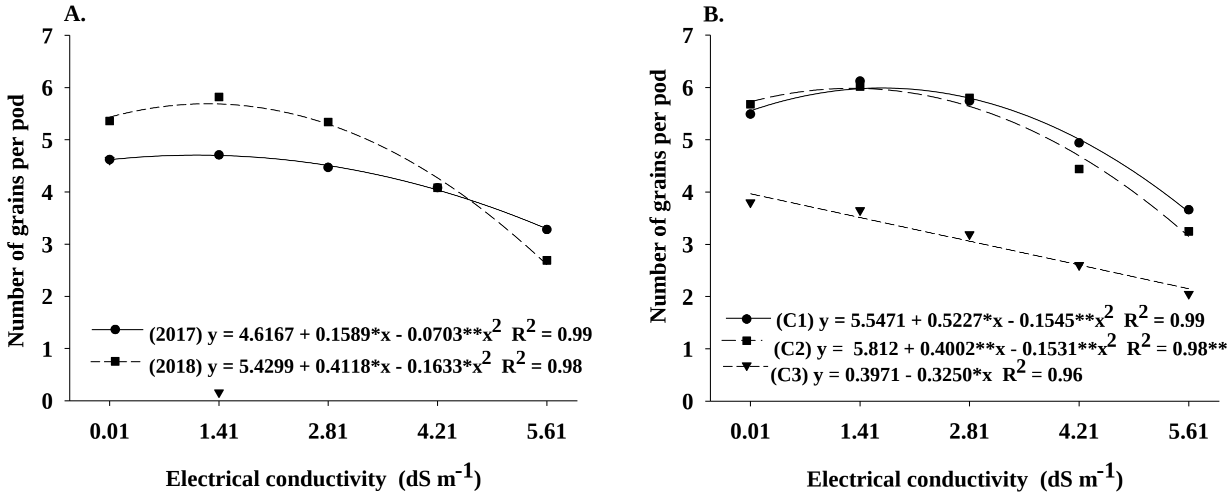

Figure 5. (A) Effects of the interaction between the electrical conductivity x year of cultivation (2017-2018) and (B) electrical conductivity x cultivars C1: BRS Tumucumaque, C2: BRS Guariba e C3: BRS Imponente) on the number of grains per pod (NGP) of cowpea 71 days after sowing (DAS). Source: Authors.

The increases in irrigation water salinity also promoted negative quadratic effects ($p<0.01$) in the EC x PC interaction on the NGP of the cultivars BRS Tumucumaque and BRS Guariba, whereas the cv. BRS Imponente showed linear decreases. The threshold salinity levels of each cultivar for this trait were obtained at the conductivities of 1.69, 1.31, and 0.01 dS m^{-1}, at which the maximum estimated yields were obtained for each cultivar: BRS Tumucumaque – 5.99, BRS Guariba – 5.98, and BRS Imponente – 3.97, respectively (Figure 9B).

The highest NGP reduction (46.1%) occurred for the cv. BRS Imponente when the electrical conductivity of irrigation water (EC) increased from the threshold salinity to 5.61 dS m^{-1}. For this same interval, the reduction of the cultivar BRS Tumucumaque (38.9%) was 15.2% lower than the average of the other two cultivars, being also 14.8% lower than the decrease observed in the cv. BRS Guariba (45.7%) and 15.5% lower than the decrease of the cv. BRS Imponente (Figure 9B). These results show that the cv. BRS Tumucumaque is more tolerant to the negative effects of increased EC levels in irrigation water than the other two cultivars for the NGP (Figure 9B).

The analysis of variance revealed a significant interaction ($p<0.05$) between the electrical conductivity of irrigation water (EC), the cultivars (C), and the years of cultivation (PC) for the number of pods per plant (NPP) and grain yield by the F-test evaluated at 71 DAS. For the 100-grain weight (GW), there were significant differences ($p<0.01$) between the electrical conductivity levels and cultivars and between the cultivars and years of cultivation. The CVs ranged from 1.42 to 7.46%, highlighting the remarkable reliability of the results obtained (Table 3).

There were significant interactions (Tukey ($p<0.05$)) between the PC and C for the number of pods per plant (NPP) of the three cultivars studied. In the first year of cultivation (2017), the cv. BRS Imponente showed the lowest mean for this parameter (3.07), followed by the cv. BRS Tumucumaque (3.38) and the cv. BRS Guariba, which showed the highest mean (3.62). This same scenario was confirmed in the second year of cultivation, with the cv. BRS Imponente maintaining the lowest mean (3.08), followed by BRS Tumucumaque (3.34) and BRS Guariba, which showed the highest mean (3.56). There were significant reductions (Tukey ($p<0.05$)) of 1.3 and 1.7% between the first and second periods of cultivation for the cultivars BRS Tumucumaque and BRS Guariba, respectively (Figure 11A).

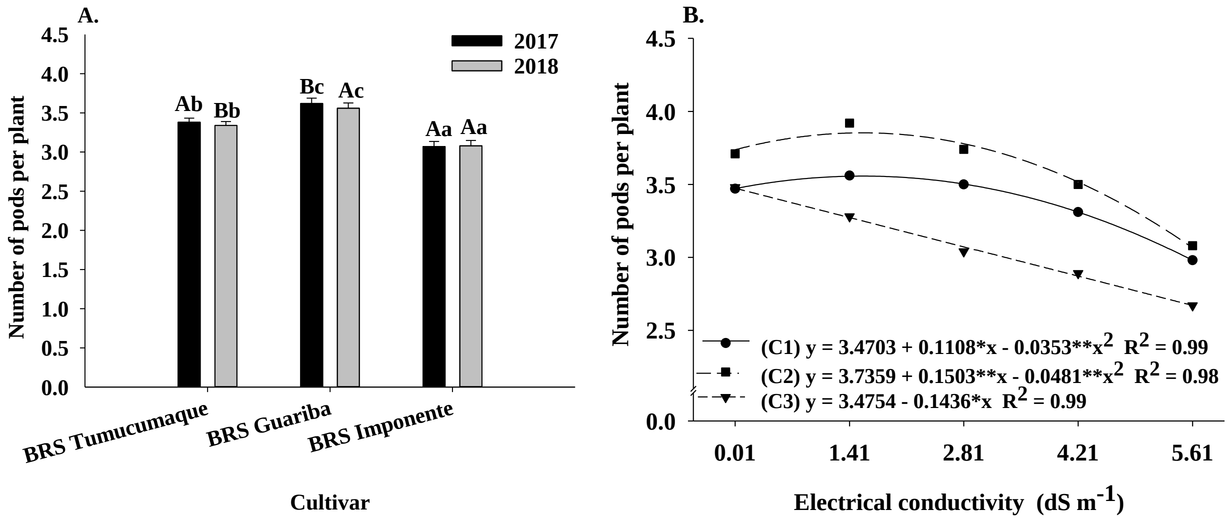

Figure 6. (A) Effects of the interaction between the cultivar x year of cultivation (2017-2018) and between (B) the electrical conductivity x cultivars on the number of pods per cowpea plant (NPP) 71 days after sowing (DAS). Equal letters (in the columns) do not differ ($p>0.05$) by the Tukey test. Uppercase letters compare periods and lowercase letters compare cultivars. Alvorada do Gurguéia, 2019. Source: Authors.

The NPP was also affected by the interaction between the EC and C. The cultivars BRS Tumucumaque and BRS Guariba showed negative quadratic effects ($p<0.01$), whereas the cv. BRS Imponente showed significant linear reductions ($p<0.01$) for this same parameter. The maximum yields estimated for the NPP of the cultivars BRS Tumucumaque (3.56), BRS Guariba (3.85), and BRS Imponente (3.47) were obtained at the electrical conductivities of 1.58, 1.56, and 0.01 dS m^{-1} applied in each year of cultivation, respectively (Figure 11B).

The highest reduction occurred in the cultivar BRS Imponente (23.1%) when the electrical conductivity of irrigation water (EC) increased from 0.01 to 5.61 dS m^{-1}. The reduction corresponded to 16.3% in the cv. BRS Tumucumaque and 20.3% in the cv. BRS when the EC increased from 1.58 and 1.56 to 5.61 dS m^{-1}. This result shows that the resistance of the cultivar BRS Tumucumaque to the negative effects of high EC levels of irrigation water is at least 25% below the mean of the other two cultivars for the NPP parameter (Figure 11B).

The NPP is one of the main production components of cowpea (Bezerra et al. 2014). From this perspective, NPP reductions in response to salinity were also observed by Assis Júnior et al. (2007).

There were significant interactions (Tukey ($p<0.05$)) between PC and C for the 100-grain weight (GW) of the three cultivars studied. In the first year of cultivation (2017), the cv. BRS Guariba showed the lowest mean (19.88 g), followed by the cv. BRS Tumucumaque (20.88 g) and the cv. BRS Imponente, with the highest mean (35.69 g). This order was confirmed in the second year, with the cv. BRS Guariba maintaining the lowest mean (20.35 g), followed by BRS Tumucumaque (20.81 g) and BRS Imponente, which showed the highest mean (35.49 g). There were significant reductions (Tukey ($p<0.05$) of 2.3% between the first and second years of cultivation for the cultivar BRS Guariba (Figure 12A).

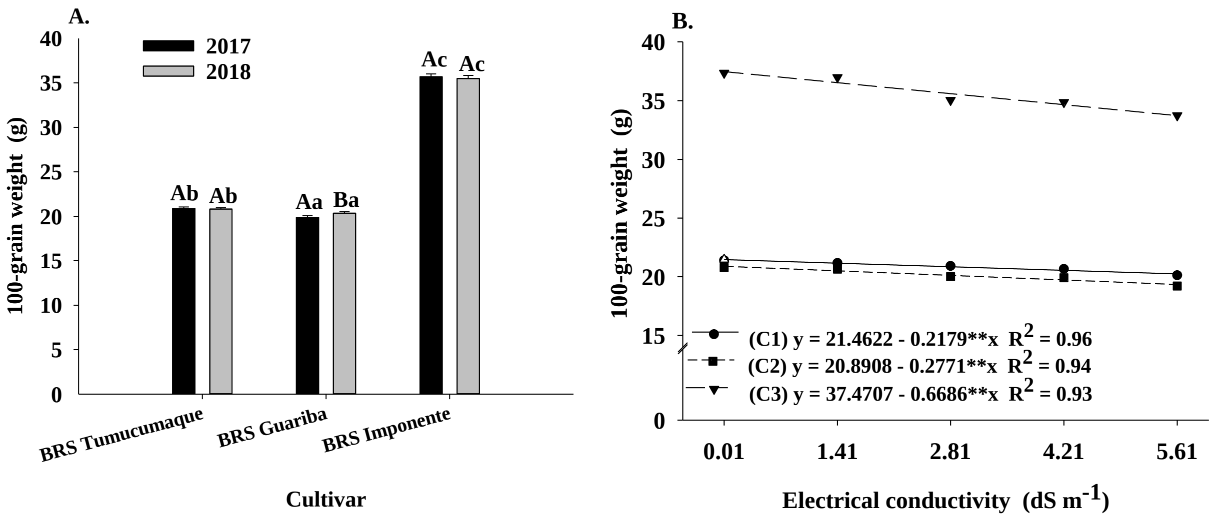

Figure 7. (A) Effects of the interaction between the cultivar x year of cultivation (2017-2018) and between (B) the electrical conductivity x cultivars on the 100-grain weight (GW) of cowpea 71 days after sowing (DAS). Cultivars: BRS Tumucumaque (C_1), BRS Guariba (C_2), and BRS Imponente (C_3). Equal letters (in the columns) do not differ ($p>0.05$) by the Tukey test. Uppercase letters compare periods and lowercase letters compare cultivars. Alvorada do Gurguéia, 2019. Source: Authors.

For the GW parameter, the three cultivars showed significant linear reductions ($p<0.01$) in the EC x C interaction. The highest reduction (10.0%) occurred in the cultivar BRS Imponente when irrigation water salinity increased from the lowest to the highest level studied. For this same interval, the reduction in the GW of the cv. BRS Tumucumaque amounted to 5.7%, whereas it was 7.4% in the cv. BRS Guariba (Figure 9B). These results demonstrate that the tolerance of the cv. BRS Tumucumaque to the increased EC of irrigation water is at least 34% lower than the mean of the other two cultivars for GW (Figure 12B).

The increases in irrigation water salinity promoted interaction between the EC and PC, with negative quadratic effects ($p<0.01$) for the grain yield of the three cowpea cultivars studied. The maximum yield values estimated in the first (743.36 kg ha^{-1}) and second cultivation cycles (770.30 kg ha^{-1}) were obtained at the EC levels of 0.57 and 0.76 dS m^{-1} of irrigation water applied in each year of cultivation, respectively. There were mean reductions of 31.4% in the first year (2017) and 38.4% in the second year (2018) when the water EC increased from 0.57 and 0.76 to 5.61 dS m^{-1}. In general, this scenario indicates a negative effect in the responses to increased irrigation water salinity (Figure 13A).

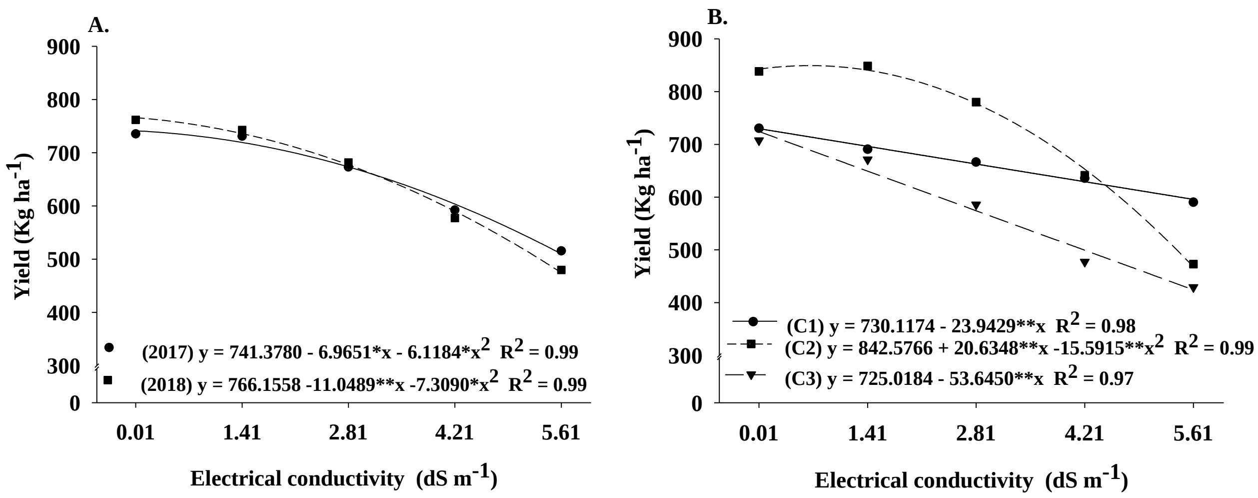

Figure 8. (A) Effects of the interaction between the electrical conductivity x year of cultivation (2017-2018) and the (B) electrical conductivity x cultivars on the grain yield of cowpea plants 71 days after sowing (DAS). Cultivars: BRS Tumucumaque (C_1), BRS Guariba (C_2), and BRS Imponente (C_3). Source: Authors.

With regard to the EC x C interaction, the cv. BRS Guariba showed negative quadratic effects ($p<0.01$) for the yield, whereas the cultivars BRS Tumucumaque and BRS Imponente showed significant linear reductions ($p<0.01$). The maximum values estimated for the yield of the cultivars BRS Tumucumaque (729.88 kg ha^{-1}), BRS Guariba (835.31 kg ha^{-1}), and BRS Imponente (724.48 kg ha^{-1}) were obtained at the electrical conductivity levels of 0.01, 1.05, and 0.01 dS m^{-1} of irrigation water applied in each treatment, respectively (Figure 13B).

The highest reduction (44.3%) in the cv. BRS Guariba occurred when the EC increased from 0.01 to 5.61 dS m^{-1}. The reduction of the cv. BRS Tumucumaque (18.4%) was 57.2% lower than the average of the other two cultivars and also 55.7% lower than the decrease of the cv. BRS Imponente (41.5%) and 44.3% lower than the decrease of the cv. BRS Guariba. This result demonstrates that the cv. BRS Tumucumaque is the most tolerant to the negative effects of increased irrigation water salinity regarding yield (Figure 13B).

At an electrical conductivity of 4.21 dS m-1, BRS Guariba achieved the same productivity as BRS Tumucumaque at this same EC level, obtaining a productivity close to the average found for Piauí for cowpea, 636 kg ha^{-1} and 666 kg ha^{-1}, respectively (Cavalcante et al., 2014), This means that this range would be a maximum limit of EC in the soil for these crops to have a reasonable production. While cv. BRS Imponente would be much more sensitive to salinity, because even with a productivity similar to cv. BRS Tumucumaque reached this productivity already at the EC level of 1.41 dS m-1.

In a study by Miranda et al. (2021) evaluating different genotypes of cowpea subjected to different salinity levels of irrigation water, in most genotypes, the decrease in dry mass was intensified by the increase in the salinity level under irrigation water, going from 4.0 to 8.0 dS m^{-1}. At a level of 8.0 dS m^{-1} (severe stress), showing a similar total dry matter accumulation among all cowpea genotypes with saline stress.

The yield reduction caused by irrigation water salinity could have occurred, in part, due to the reduction in net carbon assimilation during the flowering and fruit setting stages, associated with osmotic effects and Na^+ and Cl^- accumulation in the leaves (Assis Júnior et al. 2007), in addition to low moisture and high temperatures (Figures 2 and 3) in the plant development phases.

The reduction in biomass production as a function of increased salinity has been reported by various authors, e.g., Aquino et al. (2017), Gonçalves et al. (2014), Oliveira et al. (2013), and Tagliaferre et al. (2018). The deleterious effect of salinity on plant growth occurs due to compromised physiological and biochemical functions associated with osmotic, toxic, and nutritional effects resulting from salt accumulation in the root zone of plants (Taiz & Zeiger 2013).

These effects affect the net CO_2 assimilation, inhibit foliar expansion, and accelerate the senescence of mature leaves, thus reducing the area used for photosynthesis and the total production of photoassimilates and decreasing the growth parameters and grain production (Sá et al. 2019; Taiz & Zeiger 2013; Wu 2018).

Correlation of electrical conductivity with plant variables

Electrical conductivity did not correlate with data on the number of lateral branches and weight of one hundred grains (Figure 13). This suggests that these are variables that are little affected by the occurrence of high levels of EC, being variables related to and affected mainly by the crop genotype (Figure 7 and 12), while EC is directly affecting other variables related to the development of the crop and consequently productivity.

EC	SD	PH	NRL	NPP	CPV	NGP	GW	Yield	
1	-0.794*	-0.466*	-0.026	-0.674*	-0.132	-0.534*	-0.107	-0.752*	EC
	1	-0.113	0.487*	0.186	0.119	0.032	0.628*	0.338*	SD
		1	-0.717*	0.770*	0.220	0.855*	-0.804*	0.696*	PH
			1	-0.479*	-0.217	-0.620*	0.835*	-0.382*	NRL
				1	0.016	0.823*	-0.480*	0.895*	NPP
					1	0.310*	-0.147	0.081	CPV
						1	-0.627*	0.782*	NGP
							1	-0.339*	GW
								1	Yield

Figure 9. Pearson correlation matrix between the electrical conductivity of irrigation water, morphological variables and production of different cowpea cultivars. Source: Authors.

It is observed that soil electrical conductivity is significantly negatively correlated with the production of cowpea genotypes. Therefore, with the increase in the electrical conductivity of soils caused by the increase in sodium concentrations, this causes a reduction in crop yields. This occurs due to soil salinity interfering with crop development, in which a smaller stem diameter, plant height, number of pods per plant and number of grains per pod were also observed with increasing EC. This behavior can be caused by changes in the physical-chemical properties of the soil due to irrigation with saline water, which will affect the growth and development of crops, and consequently the yield.This effect on production can be influenced by factors such as the initial reaction in the soil, NaCl load, soil texture and crop varieties (Wang et al. 2023).

Conclusions

The results demonstrate that increased irrigation water salinity significantly compromises both the morphological development and productivity of the cowpea cultivars BRS Tumucumaque, BRS Guariba, and BRS Imponente. This response highlights the physiological sensitivity of these cultivars to dissolved salts in irrigation water. However, among the genotypes evaluated, BRS Tumucumaque exhibited greater tolerance to salinity stress with electrical conductivity levels up to 4 dS m^{-1}, with less loss of productivity.

Electrical conductivity of irrigation water is shown to be not only an indicator of water quality but also a critical variable in sustainable irrigation management. Accordingly, this study underscores the importance of incorporating salinity monitoring as a fundamental technical parameter when utilizing alternative water sources for irrigation, an essential step toward maintaining agricultural productivity and ensuring crop viability in increasingly challenging environmental conditions.

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