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Physiological indices of sour passion fruit under brackish water irrigation strategies and potassium fertilization[1]

Índices fisiológicos do maracujazeiro-azedo sob estratégias de irrigação com água salobra e adubação potássica

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HIGHLIGHTS:

Irrigation with water of 4.0 dS m^{-1} in the vegetative stage of passion fruit reduces electrolyte leakage in the leaf blade.
Chlorophyll synthesis is inhibited by salt stress, regardless of the phenological stage of plants.
Potassium does not mitigate salt stress on the gas exchange of sour passion fruit.

ABSTRACT: The objective of this study was to evaluate the physiological indices of sour passion fruit under brackish water irrigation strategies and potassium fertilization. The study was carried out under field conditions in São Domingos, PB, Brazil, using a randomized block design in a 6 × 2 factorial scheme, with treatments consisting of six brackish water irrigation strategies (irrigation with moderately saline (1.3 dS m^{-1}) water throughout the crop cycle - WS; irrigation with high-salinity (4.0 dS m^{-1}) water in the vegetative stage - VE; flowering stage - FL; fruiting stage - FR; successively in the vegetative/flowering stages - VE/FL; and vegetative/fruiting stages - VE/FR) and two doses of potassium (207 and 345 g K_2O per plant per year, corresponding, respectively, to 60 and 100% of recommendation), with four replicates and three plants per plot. Irrigation with water of 4.0 dS m^{-1} reduced the osmotic and water potentials in the leaf blade, synthesis of chlorophylls a and b, transpiration, and instantaneous carboxylation efficiency of sour passion fruit, regardless of the development stage. Salt stress in the vegetative, flowering, fruiting, and successively in the vegetative/flowering and vegetative/fruiting stages increases intercellular electrolyte leakage in sour passion fruit. Fertilization with 100% of the K recommendation increased stomatal conductance, CO_2 assimilation rate, and instantaneous water use efficiency of sour passion fruit cv. BRS GA1 under irrigation with water of 1.3 dS m^{-1} throughout the crop cycle.

Key words: *Passiflora edulis* Sims, salt stress, potassium, osmoregulation

RESUMO: Objetivou-se com este estudo avaliar os índices fisiológicos do maracujazeiro-azedo sob estratégias de irrigação com água salobra e adubação potássica. A pesquisa foi desenvolvida em condições de campo em São Domingos, PB, Brasil, utilizando-se o delineamento de blocos casualizados em esquema fatorial 6 × 2, sendo os tratamentos constituídos de seis estratégias de irrigação com águas salobras (irrigação com água de moderada salinidade (1,3 dS m^{-1}) durante todo ciclo - WS; irrigação com água de alta salinidade (4,0 dS m^{-1}) na fase vegetativa - VE; floração - FL; frutificação - FR; nas fases sucessivas vegetativa/floração - VE/FL; e vegetativa/frutificação - VE/FR) e duas doses de potássio (207 e 345 g de K_2O por planta por ano, correspondendo a 60 e 100% da recomendação), com quatro repetições e três plantas por parcela. A irrigação com água de 4,0 dS m^{-1} diminuiu o potencial osmótico e hídrico no limbo foliar, a síntese de clorofila a e b, a transpiração e a eficiência instantânea de carboxilação do maracujazeiro-azedo, independente da fase de desenvolvimento. O estresse salino na fase vegetativa, floração, frutificação e de forma sucessiva nas fases vegetativa/floração e vegetativa/frutificação aumenta o extravasamento de eletrólitos no maracujazeiro-azedo. A adubação com 100% da recomendação de K aumentou a condutância estomática, a taxa de assimilação de CO_2 e a eficiência instantânea no uso da água do maracujazeiro-azedo cv. BRS GA1 sob irrigação com água de 1,3 dS m^{-1} durante todo ciclo de cultivo.

Palavras-chave: *Passiflora edulis* Sims, estresse salino, osmorregulação, potássio

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Introduction

Sour passion fruit (*Passiflora edulis* Sims), native to Tropical America, with more than 150 species native to Brazil, has stood out among the fruit crops of economic importance in Brazil (Anuário Brasileiro de Horti & Fruti, 2022). The sour passion fruit produced in Brazil is intended for fresh consumption and the agroindustry in the preparation of carbonated and mixed beverages, syrups, jellies, dairy products, ice cream, and canned foods.

Due to climatic adversities, the cultivation of this fruit crop in the semi-arid region of northeastern Brazil is conditioned on irrigation management. However, one of the limiting factors is the quality of the available water sources. In this region, the water sources, both surface water (rivers, streams, and small and medium-sized dams) and groundwater (wells), commonly used in irrigation have high salt content (Souza et al., 2016; Dias et al., 2021).

Excess salts in water and/or soil cause physiological disorders, as well as nutritional imbalance, resulting in a reduction in plant yield (Pinheiro et al., 2022a). However, the tolerance and/or sensitivity to salinity in plants may vary between cultivars of the same species, development stage, water management strategy, salt concentration of water, and the time of exposure to salts (Lima et al., 2020a). In research on the sour passion fruit crop, Pinheiro et al. (2022a; 2022b) concluded that the cv. BRS GA1 is sensitive to salt stress applied successively in the vegetative and flowering stages.

Among the strategies to reduce the harmful effects of salt stress on plants, mineral fertilization with potassium stands out (Lima et al., 2020a; Pinheiro et al., 2022b). Potassium acts in translocation and maintenance of water balance and is involved in various biochemical and physiological functions, such as stomatal movement, enzymatic activation, protein synthesis, photosynthesis, osmoregulation, and reduction of excessive absorption of ions such as Na^+ (Ahanger et al., 2017).

The objective of this study was to evaluate the physiological indices of sour passion fruit under brackish water irrigation strategies and potassium fertilization in the first crop cycle.

Material and Methods

The experiment was carried out under field conditions at the 'Rolando Enrique Rivas Castellón' Experimental Farm, belonging to the Centro de Ciências e Tecnologia Agroalimentar - CCTA of the Universidade Federal de Campina Grande - UFCG in Pombal, PB, Brazil, located by the coordinates: 06° 48' 50" S latitude and 37° 56' 31" W longitude, at an altitude of 190 m. The data of temperature (maximum and minimum), relative humidity of the air, and precipitation during the experimental period were collected daily and are presented in Figure 1.

Six brackish water irrigation strategies - IS (WS - irrigation with moderate-salinity (1.3 dS m^{-1}) water throughout the crop cycle as a control; irrigation with high-salinity (4.0 dS m^{-1}) water only in the vegetative stage - VE; FL - flowering stage; FR - fruiting stage; successively in the vegetative and flowering stages - VE/FL; vegetative and fruiting stages - VE/FR) and two doses of potassium (207 and 345 g of K_2O per plant per year, corresponding, respectively, to 60 and 100% of the recommendation of Costa et al., 2008) were studied, distributed in randomized blocks, in a 6 × 2 factorial scheme with four replicates, and each plot consisted of three plants. The ECw levels (1.3 and 4.0 dS m^{-1}) used in the different irrigation strategies with brackish water were established based on research conducted from November 2018 to July 2019 (Lima et al., 2020b).

Irrigation strategies with brackish water were applied at the following stages of crop development: WS - irrigation with moderate-salinity water throughout the crop cycle (1-220 days after transplanting - DAT); irrigation with high-salinity water in the VE stage - from transplanting to the appearance of the floral primordium (50-113 DAT); FL - from the appearance

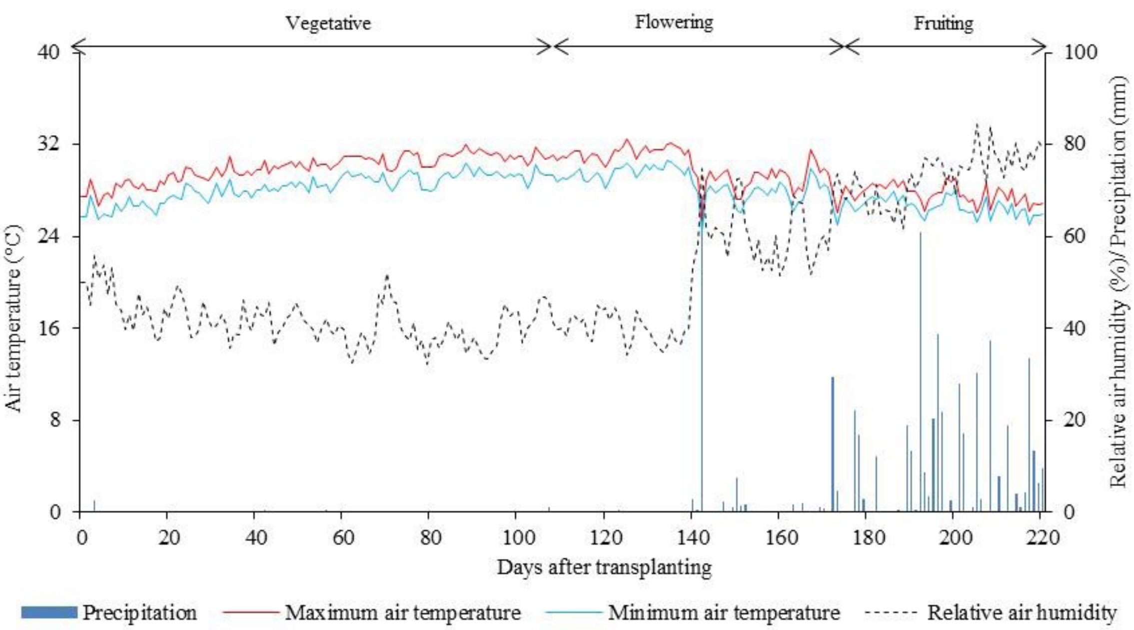


Figure 1. Data of maximum and minimum air temperature, precipitation, and average relative humidity of the air during the experimental period

of the floral primordium to the full development of the floral bud (anthesis) (114-198 DAT); FR - from the fertilization of the floral bud to the appearance of fruits with yellow spots (199-220 DAT); VE/FL - in the vegetative and flowering stages (50-198 DAT); VE/FR - in the vegetative and fruiting stages (50-113 and 199 -220 DAT).

Seeds of the sour passion fruit cv. BRS GA1 were used. Seedlings were produced by sowing two seeds in plastic bags with dimensions of 15 × 20 cm, filled with substrate, consisting (on a volume basis) of 84% of soil and 15% of sand (both autoclaved to avoid possible problems with fusariosis (*Fusarium oxysporum* f. passiflorae) during the seedling formation phase) and 1% of decomposed bovine manure. At 61 days after sowing (DAS), when the sour passion fruit seedlings started growing tendrils, transplanting to the field was carried out.

Soil tillage consisted of plowing followed by harrowing, aiming at breaking up soil clods and leveling the area. The soil of the experimental area was classified as Entisol (Fluvent) according to the United States (2014). Prior to transplanting the seedlings to the field, soil samples were collected in the experimental area in the 0-0.40 m layer and then mixed to form a composite sample, whose chemical and physical characteristics (Table 1) were obtained according to the methodology of Richards (1954).

The dimensions of the pits for transplanting the seedlings were 0.40 × 0.40 × 0.40 m. The spacing used was 3 m between rows and 3 m between plants, using the vertical trellis system with flat wire nº 14. Formative pruning, pollination, phytosanitary control, and other cultural practices were carried out according to the methodology described by Costa et al. (2008).

After opening, the pits received fertilization with 20 L of bovine manure and 50 g of single superphosphate (17% P_2O_5), as recommended by Costa et al. (2008). Nitrogen and potassium fertilizations were performed monthly via fertigation, using urea (45% N) and potassium chloride (60% K_2O) as sources of nitrogen and potassium, respectively. In the crop formation phase, 65 g of N were applied per plant and in the flowering and fruiting stages 160 g of N were applied per plant. In the plots under the 100% potassium dose, 65 g of K_2O per plant was applied in the crop formation phase (vegetative stage) and 280 g of K_2O per plant was applied in the flowering and fruiting stages, while the other plots received 60% of this dose according to treatment.

Micronutrient application was performed every two weeks using a Dripsol Micro® (Boron - 0.85%; Copper (Cu-EDTA) - 0.5%; Iron (Fe - EDTA) - 3.4%; Manganese (Mn-EDTA) - 3.2%; Molybdenum - 0.05%; Zinc - 4.2%; with 70% EDTA chelating agent) at the concentration of 1 g L^{-1}, via foliar spraying on the abaxial and adaxial sides of the leaves.

The irrigation water of the treatment with the lowest level of electrical conductivity (1.3 dS m^{-1}) came from a tube well located in the experimental area of CCTA/UFCG, whose chemical composition is presented in Table 2, whereas the water with ECw of 4.0 dS m^{-1} was obtained by the dissolution of NaCl in water from another well with ECw of 2.7 dS m^{-1}. The irrigation water with a high level of salinity was prepared considering the relationship between ECw and salt concentration (Richards, 1954), according to Eq. 1 after preparation, the electrical conductivity was checked and adjusted before use.

$$C\left(\text{mg L}^{-1}\right) \approx 640 \times \left(4 - \text{ECw}\right) \qquad (1)$$

where:

C - concentration of salts to be added (mg L^{-1}); and,

ECw - electrical conductivity of well water used (1.3 dS m^{-1}).

At 50 DAT, irrigation management with saline waters began. Irrigation was applied through a localized drip system, using 32-mm-diameter PVC tubes in the main line and 16-mm-diameter low-density polyethylene tubes in the lateral lines with drippers with a flow rate of 10 L h^{-1}. Two pressure-compensating drippers (GA 10 Grapa model) were installed for each plant, each 15 cm away from the stem. The plants were irrigated daily, at 7:00 a.m., with water according to the adopted strategy, and the water depth to be applied was estimated based on crop evapotranspiration, as described by Lima et al. (2020b).

Reference evapotranspiration (ET_0) was determined daily by the Penman-Monteith method from climatic data collected at the São Gonçalo Weather Station, located in the municipality

Table 1. Chemical and physical characteristics of the soil (0-0.40 m) of the experimental area

Chemical characteristics								
pH (H_2O) (1:2.5)	OM (dag kg^{-1})	P (mg kg^{-1})	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+
			($cmol_c$ kg^{-1})					
7.82	0.81	10.60	0.30	0.81	2.44	1.81	0	0
Chemical characteristics				**Physical characteristics**				
EC_{se} (dS m^{-1})	CEC ($cmol_c$ kg^{-1})	SAR_{se} (mmol L^{-1})$^{0.5}$	ESP (%)	Particle-size fraction (g kg^{-1})			Moisture (dag kg^{-1})	
				Sand	Silt	Clay	33.42 kPa[1]	1519.5 kPa[2]
1.52	5.36	6.67	15.11	820.90	170.10	9.00	12.87	5.29

pH - Hydrogen potential; OM - Organic matter: Walkley-Black Wet Digestion; Ca^{2+} and Mg^{2+} - Extracted with 1 M KCl at pH 7.0; Na^+ and K^+ - Extracted with 1 M NH_4OAc at pH 7.0; Al^{3+} + H^+ - Extracted with 0.5 M CaOAc at pH 7.0; EC_{se} - Electrical conductivity of the saturation extract; CEC - Cation exchange capacity, with relative contribution of Ca^{2+} = 45.5%; K^+ = 5.6%, and Mg^{2+} = 33.8%; SAR_{se} - Sodium adsorption ratio of the saturation extract; ESP - Exchangeable sodium percentage; [1,2] - Referring to field capacity and permanent wilting point, respectively

Table 2. Chemical characteristics of the moderate-salinity water used in the experiment

Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	CO_3^{2-}	Cl^-	EC	pH	SAR
($mmol_c$ L^{-1})							(dS m^{-1})		(mmol L^{-1})$^{0.5}$
0.85	0.40	5.81	0.40	5.09	0	4.07	1.30	6.69	7.34

EC - Water electrical conductivity; SAR - Sodium adsorption ratio of Sousa, PB, Brazil. The crop coefficients (Kc) used were 0.4 during the vegetative period, 0.8 during the flowering period, and 1.2 during the fruiting period for the crop according to the recommendation contained in Freire et al. (2011).

During the experiment, cultural and phytosanitary practices recommended for the crop were carried out, monitoring the emergence of pests and diseases and adopting adequate control measures when necessary, with weed control being carried out every 30 days.

At 220 days after transplanting (DAT), osmotic and water potentials in the leaf blade, relative water content, intercellular electrolyte leakage, chlorophyll a, chlorophyll b, and carotenoid (Car) contents, and gas exchanges of sour passion fruit were measured, using leaves from the middle third of the tertiary branches of the plants. Leaf osmotic potential was determined according to the methodology described by Bagatta et al. (2008). Ψ_w was measured with a Scholander pressure chamber in the leaves from the middle third of the tertiary branches with good phytosanitary conditions. To perform the measurement, the chamber was pressurized with gas until the liquid was exudated by the xylem.

Intercellular electrolyte leakage (% IEL) in the leaf blade was quantified according to Scotti-Campos et al. (2013). Relative water content (RWC) was determined using the methodology of Weatherley (1950). The contents of chlorophyll a (Chl a), chlorophyll b (Chl b), and carotenoids (Car) were determined according to the methodology of Arnon (1949).

Gas exchanges were evaluated using a median and intact leaf from the productive branch, through stomatal conductance (gs - mol H_2O m^{-2} s^{-1}), CO_2 assimilation rate (A) (μmol CO_2 m^{-2} s^{-1}), transpiration (E) (mmol H_2O m^{-2} s^{-1}) and intercellular CO_2 concentration (Ci) (μmol CO_2 m^{-2} s^{-1}) with the portable infrared carbon dioxide analyzer (IRGA), LCPro+ model from ADC BioScientific Ltda. These data were then used to calculate instantaneous water use efficiency (WUEi) (A/gs) [(μmol CO_2 m^{-2} s^{-1}) (mol H_2O m^{-2} s^{-1})$^{-1}$] and instantaneous carboxylation efficiency (CEi) (A/Ci) [(μmol CO_2 m^{-2} s^{-1}) (μmol CO_2 mol^{-1})$^{-1}$]. Readings were performed between 07:00 and 10:00 a.m., in the fully expanded leaf, under natural conditions of air temperature and CO_2 concentration, and using an artificial radiation source of 1,200 μmol m^{-2} s^{-1}, established through the curve of photosynthetic activity (Pinheiro et al., 2022a).

The data obtained were evaluated by analysis of variance by the F test after performing a normality test (Shapiro-Wilk) and checking data homogeneity. In cases of significance, the Tukey test ($p \leq 0.01$ and $p \leq 0.05$) was applied for the brackish water irrigation strategies, and the F test ($p \leq 0.05$) was applied for potassium doses, using the statistical program SISVAR version 5.6.

Results and Discussion

Potassium doses and the interaction between factors (IS × KD) did not significantly affect ($p > 0.05$) any of the analyzed variables of sour passion fruit at 220 days after transplanting (Table 3). There was a significant effect of the brackish water irrigation strategies on osmotic potential, water potential, relative water content, percentage of intercellular electrolyte leakage, and chlorophyll a, chlorophyll b, and carotenoid contents of sour passion fruit plants (Table 3). The absence of a significant effect of potassium doses on water relations (Ψo, Ψw, and RWC) and the synthesis of photosynthetic pigments in sour passion fruit may be related to the high concentration of salts in the soil solution, which interferes with potassium absorption by the roots and can also cause deformations in the cell membrane and therefore in its selectivity. In addition, other factors can also interfere with its absorption, such as water availability in the soil, pH, and level of soil compaction.

The osmotic potential in the leaf blade of sour passion fruit was significantly reduced in plants subjected to irrigation with water of 4.0 dS m^{-1} in the stages VE, FL, VE/FL, and VE/FR (Figure 2A).

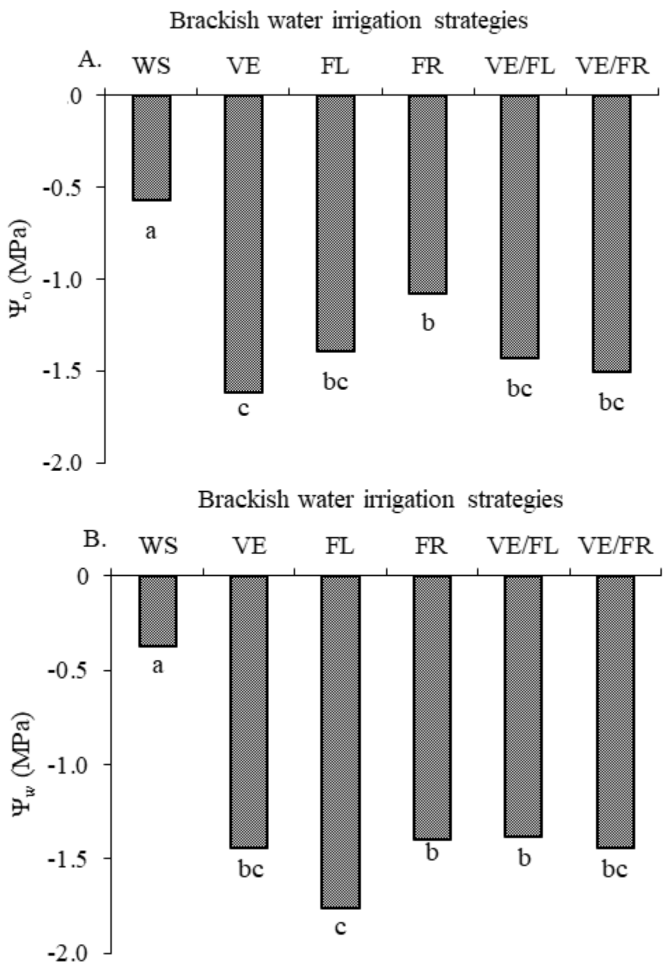
When comparing the different irrigation strategies, it was observed that the water of moderate electrical conductivity (1.3 dS m^{-1}) promoted a significantly lower decrease of Ψo in the leaf blade of sour passion fruit, being statistically superior to the other treatments. On the other hand, plants grown under high ECw in the fruiting stage differed significantly from those subjected to the VE strategy (Figure 2A). Under salt stress conditions, plants reduce their osmotic cellular potential through the synthesis of solutes in the cell cytosol (proline and soluble sugars) that play crucial roles in maintaining osmotic balance and protecting macromolecules, as well as membranes, promoting tolerance against water and/or salt stress and cellular dehydration (Tariq et al., 2018).

As observed for Ψo (Figure 2A), the Ψ_w in the leaf blade of sour passion fruit was sharply reduced by irrigation with brackish water, regardless of the phenological stage (Figure 2B). Plants under irrigation with the water of 1.3 dS m^{-1} obtained a statistically higher Ψ_w than those that received water of 4.0 dS m^{-1} in the stages VE, FL, FR, VE/FL, and VE/FR. Application of high-salinity water in FR and VE/FL resulted in higher Ψ_w

Table 3. Summary of the analysis of variance for osmotic potential (Ψo), water potential (Ψ_w), relative water content (RWC), percentage of intercellular electrolyte leakage (% IEL), chlorophyll a (Chl a), chlorophyll b (Chl b), and carotenoids (Car) of sour passion fruit cv. BRS GA1, cultivated under brackish water irrigation strategies and potassium fertilization, 220 days after transplanting

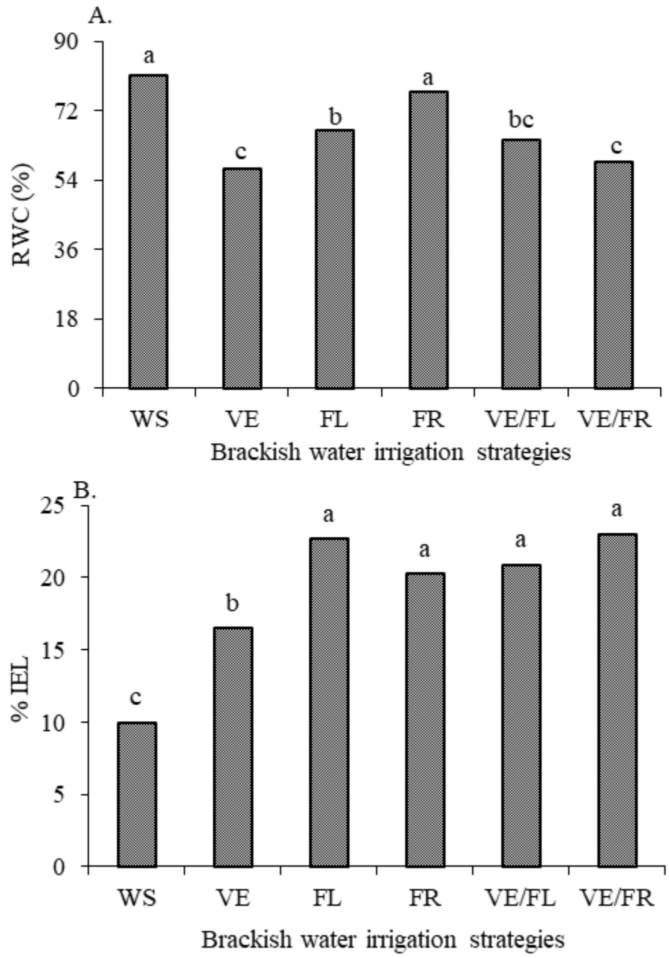
Source of variation	DF	Mean squares						
		Ψo	Ψw	RWC	% IEL	Chl a	Chl b	Car
Irrigation strategy (IS)	5	0.99**	1.20**	764.28**	196.41**	59.99**	4.52**	1.29*
Potassium doses (KD)	1	0.02ns	0.04ns	27.80ns	2.68ns	1.32ns	0.01ns	0.09ns
Interaction (IS × KD)	5	0.07ns	0.04ns	49.68ns	2.87ns	3.24ns	0.87ns	0.20ns
Blocks	3	0.07ns	0.01ns	54.43ns	11.88ns	0.67ns	1.11ns	0.17ns
Residual	33	0.08	0.05	25.92	5.49	3.47	0.55	0.28
CV (%)		22.73	17.99	7.55	12.43	17.20	25.54	14.61

DF - Degrees of freedom; CV (%) - Coefficient of variation; * - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$; ns - Not significant



Means followed by different letters indicate a significant difference between treatments by Tukey test ($p \leq 0.05$); WS - Irrigation with moderate-salinity (1.3 dS m^{-1}) water throughout the crop cycle (1-220 days after transplanting - DAT); irrigation with high-salinity (4.0 dS m^{-1}) water in VE - Vegetative stage (50-113 DAT); FL - Flowering stage (114-198 DAT); FR - Fruiting stage (199-220 DAT); VE/FL - Vegetative and flowering stages (50-198 DAT); VE/FR - Vegetative and fruiting stages (50-113/199-220 DAT)

Figure 2. Osmotic potential - Ψ_O (A) and water potential - Ψ_w (B) in the leaf blade of sour passion fruit plants cv. BRS GA1 cultivated under brackish water irrigation strategies at 220 days after transplanting



Means followed by different letters indicate significant difference between treatments by Tukey test ($p \leq 0.05$); WS - Irrigation with moderate-salinity (1.3 dS m^{-1}) water throughout the crop cycle (1-220 days after transplanting - DAT); irrigation with high-salinity (4.0 dS m^{-1}) water in VE - Vegetative stage (50-113 DAT); FL - Flowering stage (114-198 DAT); FR - Fruiting stage (199-220 DAT); VE/FL - Vegetative and flowering stages (50-198 DAT); VE/FR - Vegetative and fruiting stages (50-113/199-220 DAT)

Figure 3. Relative water content - RWC (A) and percentage of intercellular electrolyte leakage - % IEL (B) in the leaf blade of sour passion fruit plants cv. BRS GA1 cultivated under brackish water irrigation strategies at 220 days after transplanting

compared to salt stress only in the flowering stage. The decrease of Ψ_w in plants grown under high water salinity reflects the accumulation of ions in leaf tissue cells and the reduction in relative water content. The decline in Ψ_w leads to loss of turgor, inducing stomatal closure and, consequently, reduction of crop transpiration. Lima et al. (2021a), in a study evaluating the water relations of passion fruit cv. BRS RC1, as a function of the water prepared with different cations, also observed that water salinity of 3.0 dS m^{-1} consisting of sodium, sodium + calcium, and sodium + calcium + magnesium resulted in lower leaf water potential.

The relative water content (Figure 3A) in the leaf blade reflects the Ψ_w (Figure 2B). Sour passion fruit plants under irrigation with water of 1.3 dS m^{-1} throughout the cycle had higher RWC, but they did not differ significantly from those grown under ECw of 4.0 dS m^{-1} in the FR stage. Plants subjected to irrigation with water of high electrical conductivity in the stages VE and VE/FR had lower RWC than that verified in plants under the WS, FL, and FR strategies. On the other hand, plants irrigated with high-salinity water in VE/FL stages did not differ statistically ($p > 0.05$) from those irrigated with high-salinity water during the stages FL, VE/FR, and VE.

Relative water content is a determining factor for the physiological process and survival of plants, directly reflecting their water state, and its decrease indicates that salt stress resulted in a water deficit in plants, because excess salts in the soil solution cause a decrease in osmotic potential, inhibiting the absorption of water and nutrients (Behdad et al., 2021).

The intercellular electrolyte leakage in the leaf blade of sour passion fruit plants subjected to irrigation with brackish water in the stages FL, FR, VE/FL, and VE/FR was higher than that found in plants that received the water with ECw of 1.3 dS m^{-1} throughout their cycle (Figure 3B). It is important to highlight that the lowest % IEL values were obtained in plants grown under the WS and VE strategies, despite showing significant differences ($p \leq 0.05$) between them. The rupture of membrane integrity observed by electrolyte leakage in the leaf blade of sour passion fruit may have been caused by the displacement of Ca^{2+} from the cell surface by Na^+ and is a consequence of the ionic effects of salinity (Akter & Oue, 2018).

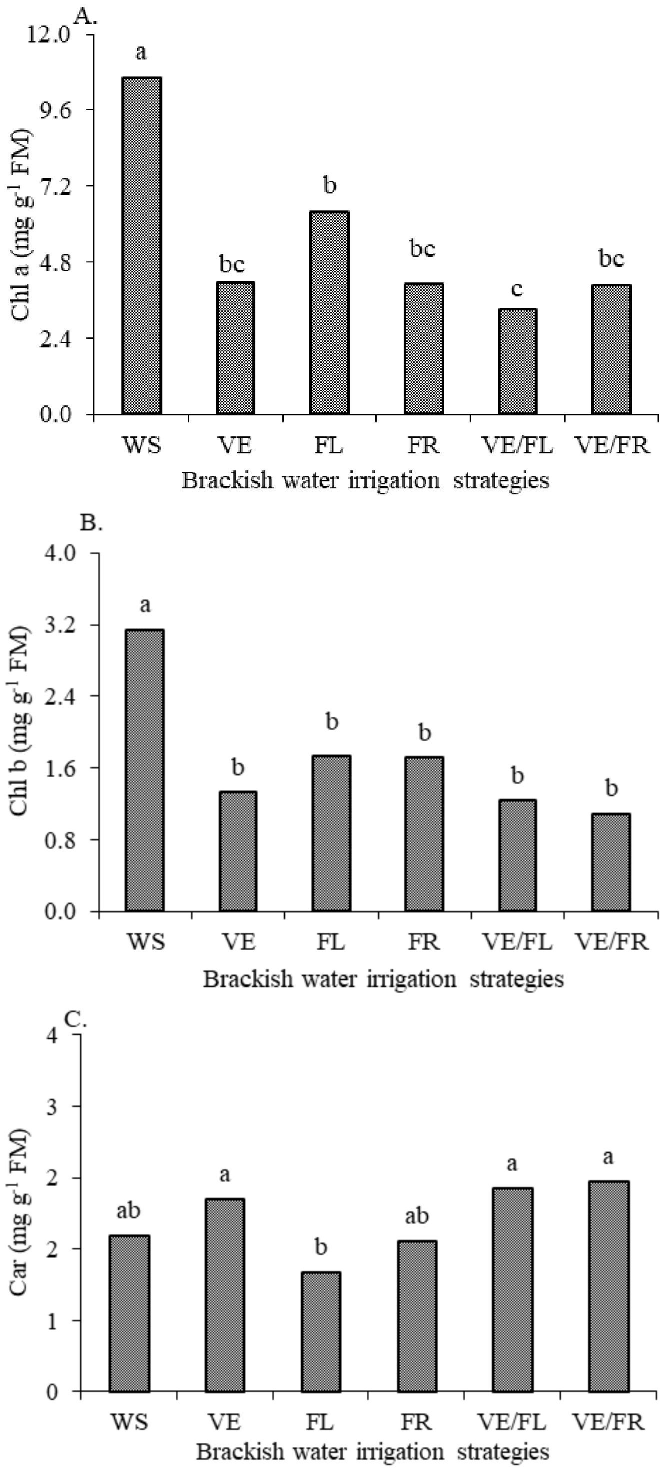
The efflux of K, which is abundant in plant cells, also contributes to increasing electrolyte leakage in the leaf blade (Hniličková et al., 2019). It is worth noting that cell membrane stability can be considered an index of cellular damage caused by the high concentration of salts because salt stress increases the production of reactive oxygen species in plants (Behdad et al., 2021).

For the chlorophyll a contents of sour passion fruit (Figure 4A), there was a significant difference among brackish water irrigation strategies, with the highest value (10.62 mg g^{-1} FM) obtained under irrigation with water of 1.3 dS m^{-1}, differing statistically ($p \leq 0.05$) from the other treatments. On the other hand, the lowest content of Chl a (3.32 mg g^{-1} FM) were observed when the water of 4.0 dS m^{-1} was applied successively in the vegetative and flowering stages (VE/FL). Plants that were irrigated with water of high electrical conductivity in the stages VE, FR, and VE/FR did not differ significantly ($p > 0.05$) from one another and from FL and VE/FL.

Salinity reduces chlorophyll content by damaging biosynthesis pathways and increasing the activity of the chlorophyllase enzyme. However, the regulation of enzymatic activity during chlorophyll biosynthesis is dependent on genotype response. In addition, the enzymatic activity of chlorophyllase and peroxidase is involved in the rapid breakdown of chlorophyll, which reduces the synthesis process (Muhammad et al., 2021). The levels of chlorophyll a and b observed here are similar to those found in studies conducted by Lima et al. (2020b) and Andrade et al. (2022) with the sour passion fruit crop cultivated under salt stress.

The chlorophyll b contents of sour passion fruit plants irrigated with water of 1.3 dS m^{-1} throughout the cycle were statistically higher than those of plants subjected to ECw of 4.0 dS m^{-1} in the different stages (Figure 4B). When comparing the Chl b contents of plants subjected to irrigation with ECw of 4.0 dS m^{-1} in the different stages of development, no significant difference was observed between treatments. The reduction in Chl b contents in plants subjected to salt stress may be related to inhibition of the synthesis of 5-aminolevulinic acid, a chlorophyll precursor, and/or increased activity of chlorophyllase enzyme, which degrades chlorophyll (Gomes et al., 2017). It is important to highlight that salt stress causes direct and indirect effects on chlorophyll synthesis. Direct effects are related to the regulation of levels of activity and expression of enzymes involved in chlorophyll biosynthesis, whereas indirect effects are achieved by specific regulatory pathways, such as antioxidant enzyme systems (Yang et al., 2019).

Regarding carotenoid contents (Figure 4C), salt stress applied in the VE, VE/FL, and VE/FR stages significantly increased the Car contents only in plants grown under ECw of 4.0 dS m^{-1} in the flowering stage. However, when comparing plants subjected to irrigation with water of 1.3 dS m^{-1} throughout the cycle to those that received the highest salinity level in the VE, FL, FR, VE/FL, and VE/FR stages, no significant differences were observed between them. Carotenoids, being antioxidants, have the potential to detoxify plants from the effects of reactive oxygen species or protect the lipids of the plasma membrane from oxidative stress generated in plants exposed to salinity (Gomes et al., 2017). In a study carried out with the sour passion fruit 'BRS GA1' in the seedling formation phase, Lima et al. (2020a) also found that an increase in water salinity from 0.3 to 3.5 dS m^{-1} increased carotenoid synthesis, standing out as a protective mechanism against oxidative reactions.



Means followed by different letters indicate significant difference between treatments by Tukey test ($p \leq 0.05$); WS - Irrigation with moderate-salinity (1.3 dS m^{-1}) water throughout the crop cycle (1-220 days after transplanting - DAT); irrigation with high-salinity (4.0 dS m^{-1}) water in VE - Vegetative stage (50-113 DAT); FL - Flowering stage (114-198 DAT); FR - Fruiting stage (199-220 DAT); VE/FL - Vegetative and flowering stages (50-198 DAT); VE/FR - Vegetative and fruiting stages (50-113/199-220 DAT); FM - Fresh mass

Figure 4. Contents of chlorophyll a - Chl a (A), chlorophyll b - Chl b (B), and carotenoids - Car (C) of sour passion fruit cv. BRS GA1, cultivated under brackish water irrigation strategies at 220 days after transplanting

Table 4. Summary of the analysis of variance for stomatal conductance (gs), internal CO_2 concentration (Ci), transpiration (E), CO_2 assimilation rate (A), instantaneous water use efficiency (WUEi), and instantaneous carboxylation efficiency (CEi) of 'BRS GA1' sour passion fruit cultivated under brackish water irrigation strategies and potassium fertilization, at 220 days after transplanting

Source of variation	DF	Mean squares					
		gs	Ci	E	A	WUEi	CEi
Irrigation strategy (IS)	5	0.271**	12134.52**	2.50**	51.73**	0.0016**	0.00009**
Potassium doses (KD)	1	0.006^{ns}	330.75^{ns}	0.02^{ns}	11.61*	0.0001^{ns}	0.000003^{ns}
Interaction (IS × KD)	5	0.014*	2743.98^{ns}	0.20^{ns}	15.40*	0.0002*	0.000005^{ns}
Blocks	3	0.003^{ns}	485.95^{ns}	0.81^{ns}	5.76^{ns}	0.000005^{ns}	0.000009^{ns}
Residual	33	0.002	1318.35	0.18	2.03	0.00005	0.000004
CV (%)		27.53	11.98	17.77	15.77	22.22	22.80

DF - Degrees of freedom; CV (%) - Coefficient of variation; * - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$; ^{ns} - Not significant

The interaction between factors (IS × KD) significantly influenced the stomatal conductance, CO_2 assimilation rate, and instantaneous water use efficiency of sour passion fruit cv. BRS GA1, at 220 days after transplanting (Table 4). There was a significant effect of brackish water irrigation strategies on gs, Ci, E, A, WUEi, and CEi of 'BRS GA1' sour passion fruit (Table 4). Potassium doses significantly affected only the CO_2 assimilation rate.

The stomatal conductance of sour passion fruit was significantly affected ($p \leq 0.05$) by the interaction between factors - IS × KD (Figure 5A). Irrigation with water of 1.3 dS m^{-1} throughout the cycle resulted in statistically higher gs compared to plants subjected to salt stress in the other stages for both K doses. When comparing the gs of plants subjected to ECw of 4.0 dS m^{-1} in the stages VE, FL, FR, VE/FL, and VE/FR, no significant differences were observed among them for both K doses.

The decrease in water absorption caused by increased salinity, as observed for Ψ_w in the leaf blade of sour passion fruit (Figure 2B), induces stomatal closure to minimize water loss to the atmosphere. Thus, one of the consequences of stomatal closure caused by salt stress is the reduction of water vapor flow, in order to maintain leaf water potential and prevent the dehydration of guard cells, which results in the restriction of the normal flow of CO_2 in leaf mesophyll cells, impairing the transpiration and CO_2 assimilation of the plants (Lima et al., 2020a). In the analysis of K doses considering each brackish water irrigation strategy (Figure 5A), plants fertilized with 100% K_2O showed higher gs when they were irrigated with ECw of 1.3 dS m^{-1} throughout the cycle. In the other irrigation strategies, there were no significant differences between K doses, regardless of the phenological stage.

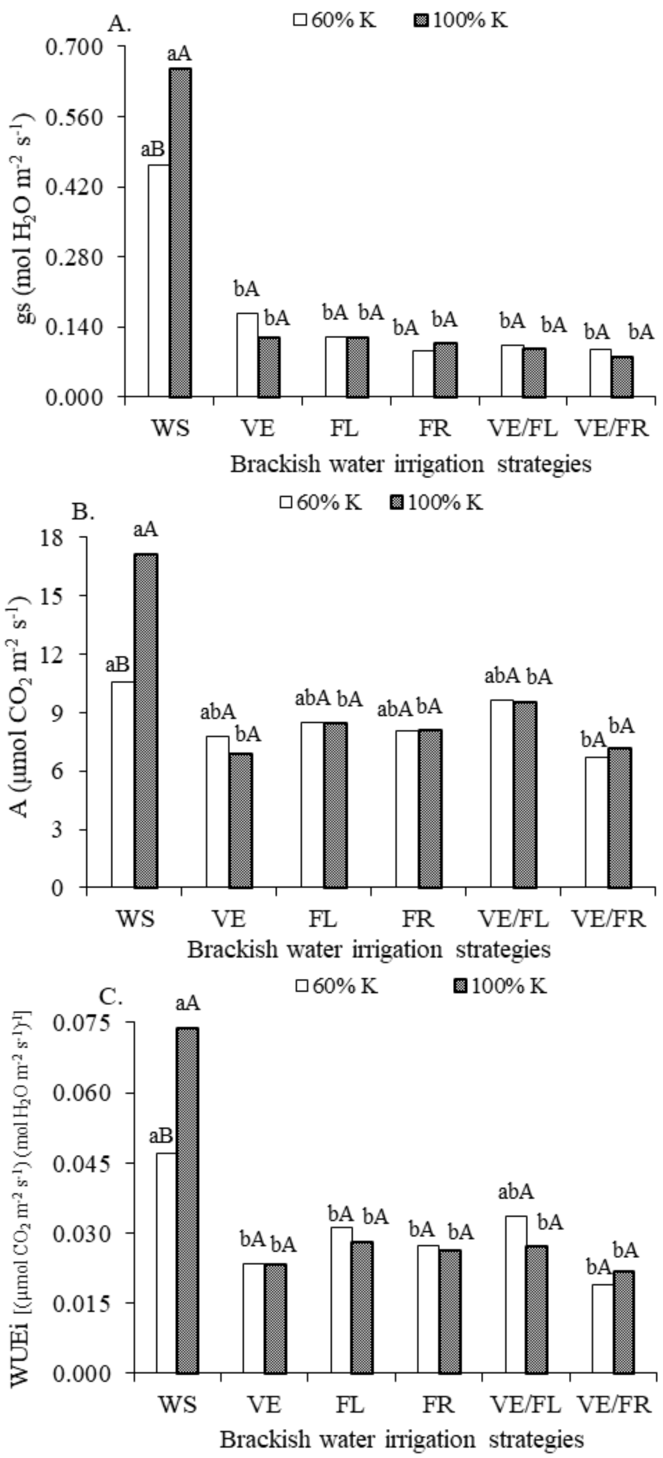
The CO_2 assimilation rate - A (Figure 5B) of sour passion fruit plants under irrigation with water of 1.3 dS m^{-1} throughout the cycle differed significantly from the value of those subjected to ECw of 4.0 dS m^{-1} in the other stages for both K doses. When comparing the A values of plants grown under salt stress in the stages VE, FL, FR, VE/FL, and VE/FR, no significant differences were observed among them for both K doses. The decrease in CO_2 assimilation rate induced by salt stress is associated with an accentuated decline in gs and, consequently, in E, highlighting the action of stomatal factors on the gas exchange activities of plants irrigated with a high-salinity water (Pinheiro et al., 2022a). In addition to stomatal factors, non-stomatal factors such as negative regulation of photosynthetic enzymes of the Calvin cycle, disturbances in chlorophyll biosynthesis, and damage to the photosynthetic apparatus caused by oxidative stress also contribute to a reduction in CO_2 assimilation (Pan et al., 2020).

When analyzing the effects of K doses considering each brackish water irrigation strategy, it was verified that plants subjected to 100% of the recommendation of Costa et al. (2008) stood out with higher net photosynthetic rate under irrigation with water of 1.3 dS m^{-1} compared to those fertilized with 60% K, indicating greater efficiency in the use of potassium by the sour passion fruit cultivated with water of moderate salinity level throughout the cycle (WS). On the other hand, the absence of positive effects on plants that received the water of 4.0 dS m^{-1} in the different phenological stages may be related to the intensification of salt stress by the potassium source used in this study, given that it has a high salt index (116) and high concentration of chloride in its composition.

The instantaneous water use efficiency of sour passion fruit plants was also significantly ($p \leq 0.05$) affected by the interaction between factors (Figure 5C). Sour passion fruit plants subjected to irrigation with ECw of 1.3 dS m^{-1} throughout the crop cycle obtained a statistically higher WUEi for both K doses compared to those that received the water of 4.0 dS m^{-1} in the stages VE, FL, FR, VE/FL, and VE/FR. WUEi refers to the amount of CO_2 fixed by the plant for each unit of water that is lost in this process. It is important to highlight that the absorption of CO_2 from the external environment by the stomata also results in water loss and the plant, in order to reduce this loss, restricts the entry of CO_2 into the substomatal chamber (Suassuna et al., 2014).

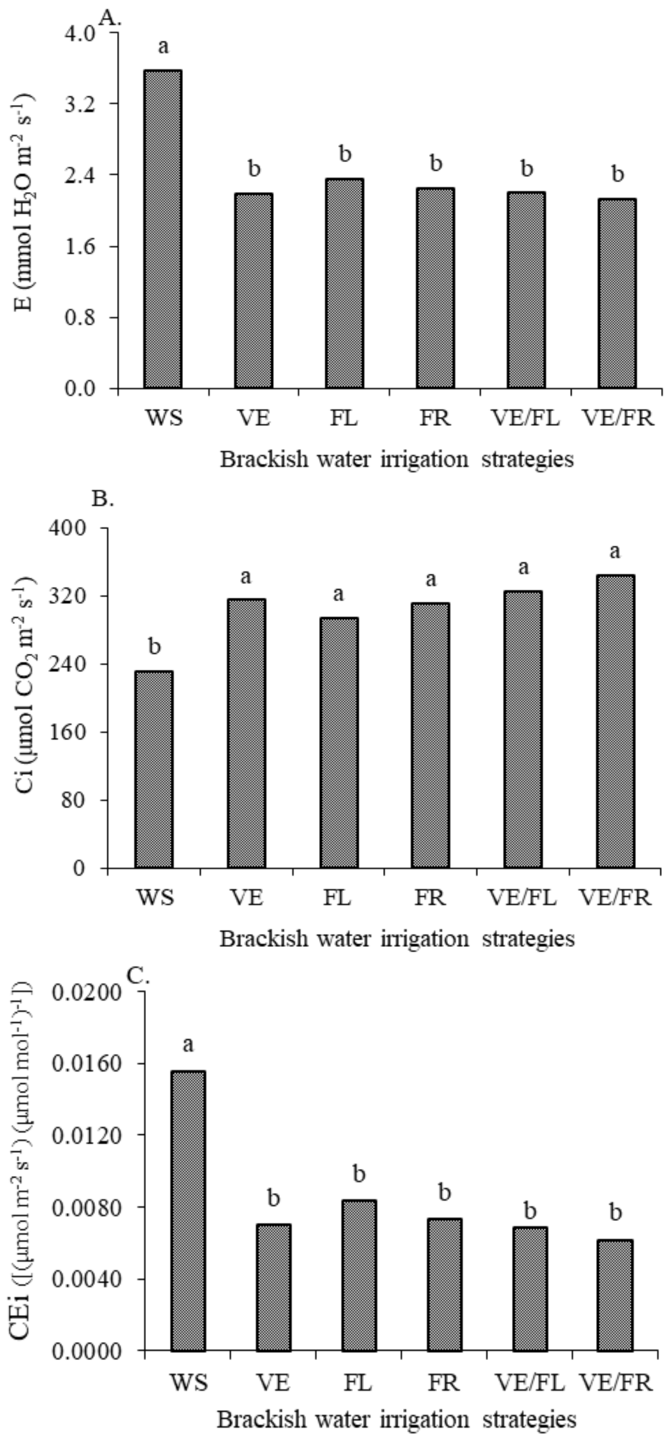
Unlike the results obtained in this study, Lima et al. (2020b) evaluated the gas exchange of sour passion fruit cv. BRS RC1 as a function of irrigation with saline waters (ECw: 0.3 to 3.5 dS m^{-1}) in the seedling formation phase and verified that WUEi was not significantly influenced by ECw of up to 3.5 dS m^{-1}, 40 days after sowing. As observed for gs and A, WUEi was significantly affected only in the WS strategy, and plants under the dose of 60% stood out with the lowest value.

Irrigation with water of high electrical conductivity (4.0 dS m^{-1}) in the stages VE, FL, FR, VE/FL, and VE/FR significantly reduced leaf transpiration (Figure 6A) in sour passion fruit plants compared to those cultivated under the moderate level of water salinity throughout the cycle. It is observed that plants subjected to salt stress reduce their leaf transpiration, regardless of the phenological stage. The reduction of transpiration in plants grown under salt stress in the different phenological stages may also be related to stomatal closure, observed in this



Bars with the same uppercase letters indicate no significant differences between potassium doses in the same brackish water irrigation strategy, and bars with the same lowercase letters for the same potassium dose indicate no significant differences between the brackish water irrigation strategies (Tukey test, $p \leq 0.05$); WS - Irrigation with moderate-salinity (1.3 dS m^{-1}) water throughout the crop cycle (1-220 days after transplanting - DAT); irrigation with high-salinity (4.0 dS m^{-1}) water in VE - Vegetative stage (50-113 DAT); FL - Flowering stage (114-198 DAT); FR - Fruiting stage (199-220 DAT); VE/FL - Vegetative and flowering stages (50-198 DAT); VE/FR - Vegetative and fruiting stages (50-113/199-220 DAT)

Figure 5. Stomatal conductance - gs (A), CO_2 assimilation rate - A (B), and instantaneous water use efficiency - WUEi (C) of sour passion fruit cv. BRS GA1 as a function of the interaction between brackish water irrigation strategies and potassium doses at 220 days after transplanting



Means followed by different letters indicate significant difference between treatments by Tukey test ($p \leq 0.05$); WS - Irrigation with low-salinity water throughout the crop cycle (1-220 days after transplanting - DAT); WS - Irrigation with moderate-salinity (1.3 dS m^{-1}) water throughout the crop cycle (1-220 days after transplanting - DAT); irrigation with high-salinity (4.0 dS m^{-1}) water in VE - Vegetative stage (50-113 DAT); FL - Flowering stage (114-198 DAT); FR - Fruiting stage (199-220 DAT); VE/FL - Vegetative and flowering stages (50-198 DAT); VE/FR - Vegetative and fruiting stages (50-113/199-220 DAT)

Figure 6. Transpiration - E (A), internal CO_2 concentration - Ci (B), and instantaneous carboxylation efficiency - CEi (C) of sour passion fruit cv. BRS GA1, cultivated under different brackish water irrigation strategies at 220 days after transplanting

study by the decrease in stomatal conductance (Figure 5A). The osmotic stress resulting from the accumulation of salts in the soil solution reduced the plant's capacity to absorb water, while ionic toxicity increases with the excessive accumulation of salts through the transpiration flow, which hampers leaf cells (Akter & Oue, 2018).

Lima et al. (2021b), in a study evaluating the gas exchange of passion fruit cultivars under irrigation with waters of different salinity levels (ECw ranging from 0.3 to 3.5 dS m^{-1}), observed that transpiration decreased with increasing levels of electrical conductivity of water from 0.3 dS m^{-1}. As observed by Lima et al. (2021b), the reduction in leaf transpiration in plants subjected to salt stress stands out as a strategy for maintaining cellular water potential and reducing excessive absorption of toxic ions to plant metabolism.

For the internal CO_2 concentration - Ci (Figure 6B), sour passion fruit plants under irrigation with water of 4.0 dS m^{-1} in the stages VE, FL, FR, VE/FL, and VE/FR showed no significant differences from one another and differed from plants that received the water of 1.3 dS m^{-1} throughout the crop cycle. The highest Ci values were obtained under conditions of irrigation with water of high electrical conductivity, regardless of the development stage of the crop. The increase of Ci in plants grown under salt stress indicates that non-stomatal factors also influenced the photosynthetic activity of plants, such as the low activity of the enzyme Ribulose-1,5-bisphosphate carboxylase/oxygenase (Hussain et al., 2012), a situation confirmed by the CEi (Figure 6C).

The instantaneous carboxylation efficiency of sour passion fruit plants (Figure 6C) subjected to salt stress in the stages VE, FL, FR, VE/FL, and VE/FR was significantly reduced compared to those under irrigation with ECw of 1.3 dS m^{-1}. It was verified (Figure 6C) that the use of water by plants irrigated with electrical conductivity of 4.0 dS m^{-1} in any stage interferes negatively with the CEi of sour passion fruit. The decline in instantaneous carboxylation efficiency induced by salt stress is indicative of a reduction in the production of $NADP^+$ (electron acceptor in photosystem I (PSI)), increasing the electron pool in the electron transport chain (Hasanuzzaman et al., 2020).

Conclusions

1. Irrigation using water with electrical conductivity of 4.0 dS m^{-1}, regardless of the development stage, reduced osmotic and water potentials in the leaf blade, chlorophyll synthesis, transpiration, and instantaneous carboxylation efficiency of sour passion fruit.

2. The salt stress caused by water salinity of 4.0 dS m^{-1} in the vegetative stage reduces intercellular electrolyte leakage in the leaf blade of sour passion fruit cv. BRS GA1.

3. Fertilization with 100% of K recommendation (345 g per plant per year) increases stomatal conductance, CO_2 assimilation rate, and instantaneous water use efficiency of sour passion fruit cv. BRS GA1 cultivated under irrigation with 1.3 dS m^{-1} water throughout the crop cycle.

4. Potassium fertilization does not alleviate the effects of salt stress on the physiological indices of sour passion fruit.

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